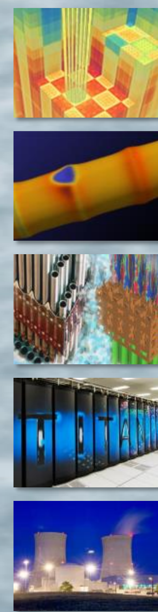
CASL Technical Accomplishments Past 12 Months

Jess Gehin & Paul Turinsky

CASL Joint IC/SC Annual Meeting
Oak Ridge National Laboratory
November 4-5, 2015



The Consortium for Advanced Simulation of LWRs
A DOE Energy Innovation Hub

U.S. DEPARTMENT OF ENERGY

Agenda-IC/SC: Wednesday AM & PM

8:00	Check In (Building 5200, Visitor's Center)	
8:30	CASL technical accomplishments past 12 months	Jess Gehin Paul Turinsky
9:45	*Break*	
10:00	VERA-CS: Performance and Validation	Scott Palmtag
11:00	Spotlight on VMA Focus Area: UQ & Data Assimilation Activities	Ralph Smith
12:00	Working Lunch – Status of Market Assessment and Post-CASL Organization Planning	Sara Edge
1:00	Spotlight on Thermal Hydraulic Focus Area: CFD Progress & Path Forward	Emilio Baglietto
2:00	Status of Challenge Problems – Progress Made: Overview & CRUD	Zeses Karoutas Jeff Secker Gregg Swindelhurst
3:00	*Break*	
3:15	Status of Challenge Problems – Progress Made: PCI and DNB	Joe Rashid Brian Wirth Yixing Sung
4:15	BWR Simulation Progress: CTF and MPACT	Robert Salko Scott Palmtag
4:45	CASL Phase 2 Light Federal Touch	Alex Larzelere
5:00	Adjourn	

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Agenda-IC: Thursday AM

8:30	Welcome and Introductions	Scott Thomas
9:00	Update on Application of VERA to AP-1000	Fausto Franceschini
9:40	Test Stands – AREVA Test Stand – TVA Test Stand	Steve Hess Chris Lewis Rose Montgomery
10:45	*Break*	
11:00	VERA User Group	Rose Montgomery
11:45	Working Lunch-VERA Licensing and Release Process	Matt Sieger
12:45	SMR Vendor Plans and Perspectives	Dan Ingersoll
1:15	Open Comments for IC meeting	Steve Hess
1:30	Break	

Agenda-SC: Thursday AM

7:45	Bus to Building 5700 - Meet in SNS-Building 8600 Lobby	
8:00	Update on FY15 Performance and FY16 Plans	Jess Gehin/Paul Turinsky
8:30	Progress and Planning for Codes & Challenge Problems V&V	Vince Mousseau
9:00	50/30/20 Funding Split: SC Recommendation versus Actual	Paul Turinsky
9:30	Charge to Science Council regarding S&T Annual Review	Bill Oberkampf (Chair)
9:50	Break and Relocation to Breakout Meetings	
10:10	Breakout Meetings with Focus Area Leads: Response to Science Council Recommendations	Science Council and FA Leads
12:00	Science Council Working Meeting on S&T Annual Review Preparation, *working lunch*	Science Council
1:30	Bus back to SNS-Building 8600	

Agenda-IC/SC: Thursday PM

1:45	*Science Council Joins Industry Council* Industry Council Round Robin **(opportunity for individual IC members to comment)**	All Industry Council Members
2:45	Industry Council Action Items	Steve Hess
3:00	Science Council Out Briefing of Major Findings	Bill Oberkampf (Chair)
4:00	Adjourn	

Outline

- Summary of Changes in CASL Organization
- Progression of progress on Core Simulator
- Progression of progress on CIPS Challenge Problem
- Key milestones for PCMI, DNB Challenge Problems
- Assessment of CFD and Path Forward
- Progress on V&V
- Advances in Fundamental Understanding
- FY16 Plans – DOE Reportable Milestones

Changes in Organization

- Administration
  - Linda Weltman (ORNL) transfers within ORNL out of CASL
  - Lorie Fox (ORNL) transfers within ORNL into CASL
- Fuel, Materials and Chemistry (FMA)
  - Lead Chris Stanek (LANL) assumes National Technical Director of NEAMS
  - Brian Wirth (UTK) moved from Deputy to Lead and David Andersson (LANL) assumes Deputy position
- Thermal-Hydraulic Methods (THM)
  - Acting Lead Marcus Berndt (LANL) concludes interim term
  - Emilio Baglietto (MIT) moved from Deputy to Lead and David Pointer (ORNL) assumes Deputy position (previously NEAMS integration lead)
- Technology Deployment & Outreach (TDO)
  - Lead Dennis Hussey (EPRI) being reassigned by EPRI and leaving CASL
  - New Lead not yet assigned
- Challenge Problem Integrator (CPI)
  - Joe Rashid (Anatech) taking place of Rob Montgomery (PNNL) as PCI CPI

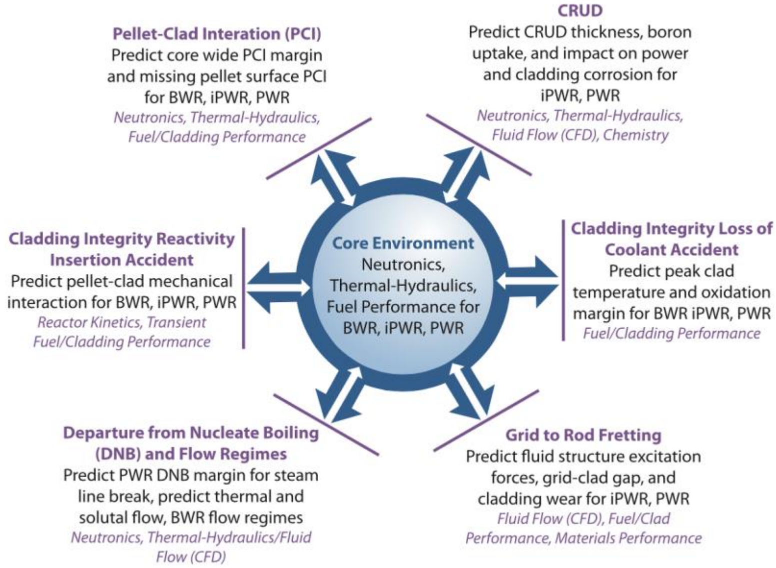
FY15 Performance

CASL Year 5 (FY15) Milestone Status: Oct 2014 – Sept 2015

Reportable #	Milestone ID	Milestone Description	Finish Date	Owner	Status
FY15.CASL.001	L3:SLT.MGMT.P10.01	Develop and document the CASL Management and Operations Plan for Phase 2	Dec 2014	Doug Kothe	Completed
FY15.CASL.002	**L1:CASL.P10.01**	**Demonstrate VERA-CS capabilities for a representative iPWR core**	Feb 2015	Rose Montgomery	Completed
FY15.CASL.003	L2.PHI.P10.01	Validate VERA-CS against the industry standard BEAVRS cycle depletion benchmark problem	Mar 2015	Ben Collins	Completed
FY15.CASL.004	L2:TDO.P10.01	Develop a preliminary deployment strategy for VERA that includes options for a post-CASL entity	Mar 2015	Dennis Hussey	Completed
FY15.CASL.005	**L1:CASL.P11.02**	**Qualify VERA-CS for a multi-cycle (w/fuel-reloading) PWR core simulation capability**	Jun 2015	Andrew Godfrey	Completed
FY15.CASL.006	L2:RTM.P10.01	Demonstrate a BWR subregion neutronics capability using a planar pin-resolved MOC methodology	July 2015	Brendan Kochunas	Completed
FY15.CASL.007	L2:VMA.VUQ.P11.04	Demonstrate an uncertainty quantification analysis of VERA-CS for a PWR fuel assembly with depletion	Sept 2015	Vince Mousseau	Completed
FY15.CASL.008	**L1:CASL.P11.03**	**Qualify a core-wide PWR CIPS capability that includes an initial corrosion product treatment**	Sept 2015	Jeff Secker	Completed
FY15.CASL.009	L2:FMC.P11.01	Demonstrate 3D PCI analysis with BISON-CASL on a relevant operating plant that experienced PCI failures	Sept 2015	Brian Wirth	Completed
FY15.CASL.010	L2:THM.P11.02	Experimenetally determine the effects of CRUD on sub-cooled boiling	Sept 2015	Jacopo Buongiorno	Completed
FY15.CASL.011	L3:THM.CFD.P11.07	Document the progress made on developing multi-phase capabilities in Hydra-TH	Sept 2015	Mark Christon	Completed

All DOE Deliverable Milestones Completed

Challenge Problems Progress



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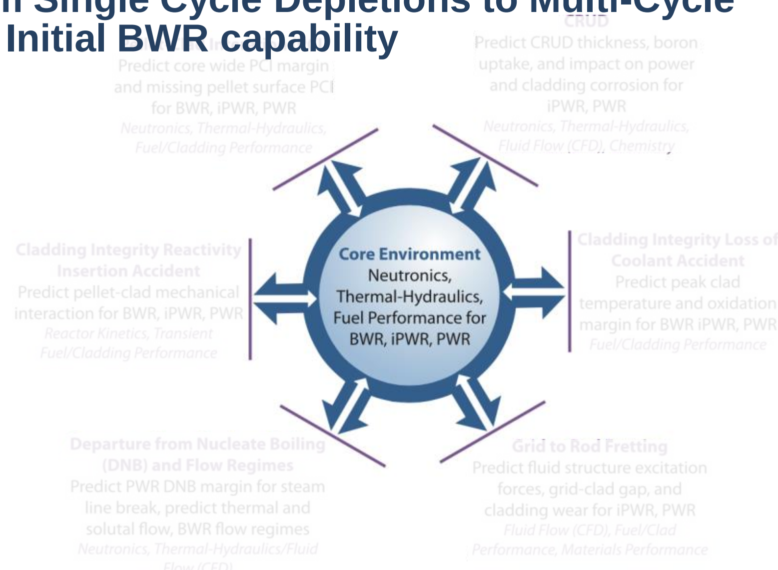
Progress on Core Simulator: From Single Cycle Depletions to Multi-Cycle and Initial BWR capability



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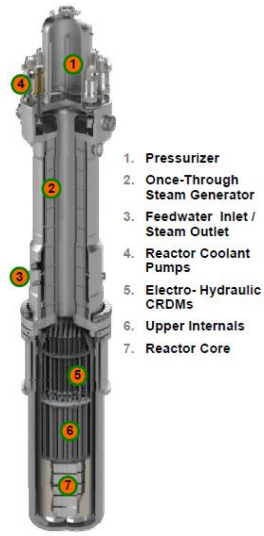
February 2015

VERA-CS Application to iPWR

Milestone FY15.CASL.002

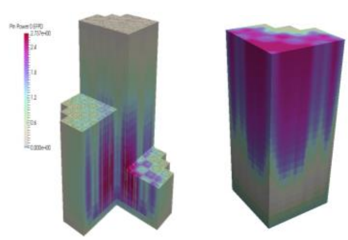
- Purpose: Demonstrate VERA-CS application to an iPWR (*mPower-like core which utilizes control rods for shim)*
- Tool: VERA-CS core simulator
- Results:
  - VERA-CS can address different core configurations, with exception pin and assembly layouts must currently fall on Cartesian grid
  - Solutions for multiple rodded configurations found robust
  - Illustrated the capabilities of VERA-CS to develop a control component management strategy

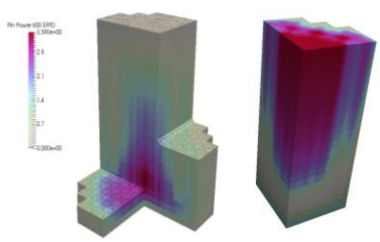


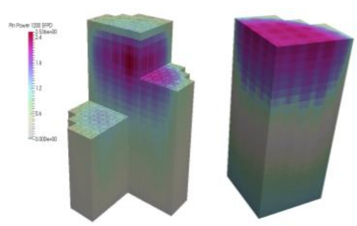
Application of Single Cycle Depletion Capabilities

Control Banks and Power Density & Coolant Temperature

			B9	B10	B9			
	B9	B5	B8	B4	B8	B5	B9	
	B5	B3	B7	B8	B7	B3	B5	
B9	B8	B7	B2	B1	B2	B7	B8	B9
B10	B4	B1	B8	B6	B8	B1	B4	B10
B9	B8	B7	B2	B1	B2	B7	B8	B9
	B5	B3	B7	B8	B7	B3	B5	
	B9	B5	B8	B4	B8	B5	B9	
			B9	B10	B9			







March 2015

VERA-CS Benchmarking & Verification

Milestone FY15.CASL.003

- Purpose: Validate VERA-CS using industry standard BEAVRS benchmark problem (*4-loop WEC core*).
- Tool: VERA-CS core simulator
- Results:
  - Power distributions, control rod worths and ITC agreed well with plant data.
  - Critical boron deviates more than expected (up to 50 ppm) as the cycle burns.

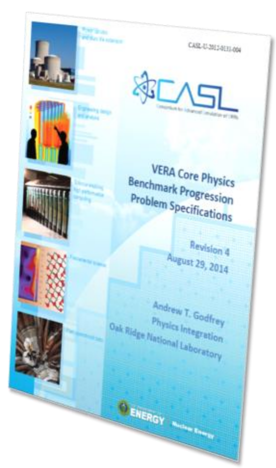
Drove Development of Shuffling Capabilty

March 2015

Completion of Core Physics Progression Problems

L3:RTM.PRT.P9.04

- Created May 2011 for application-based development and testing
- ~75 CE Monte Carlo (KENO-VI) reference solutions for Problems 1-5
- Measured data for Problems 5, 9, & 10
- Specifications and solutions publicly available
- Revision 4 released 8/2014
- Problems 1-10 completed and solved with VERA-CS in 2015



Very successful for Driving Development

Validation of VERA-CS with Plant Data

June 2015

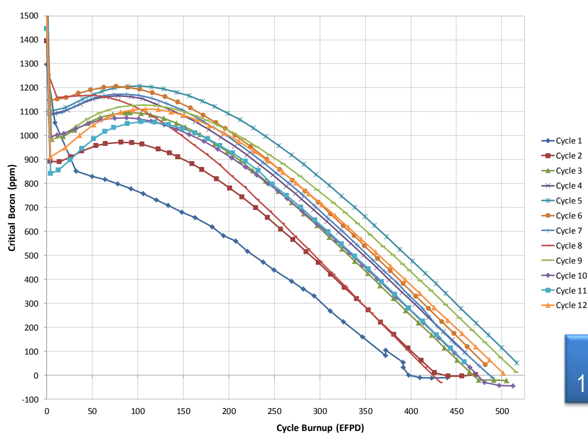
Milestone FY15.CASL.005

- Purpose: Validate core reactivity and power distribution predictions using all operating cycles of Watts Bar Unit 1 (12 cycles involved) and demonstrate CASL core simulator capabilities.
- Tool: VERA-CS core simulator
- Results:
  - Comparisons between predicted and measured critical boron values and power distributions were good except when CIPS occurred (i.e. Cycle 7).
  - Usage of VERA-CS was shown to be straight forward and robust over many reload cycles.

Marked Completion of Implementation of Primary PWR Core Simulator Features

WBN1 HFP Boron Letdown

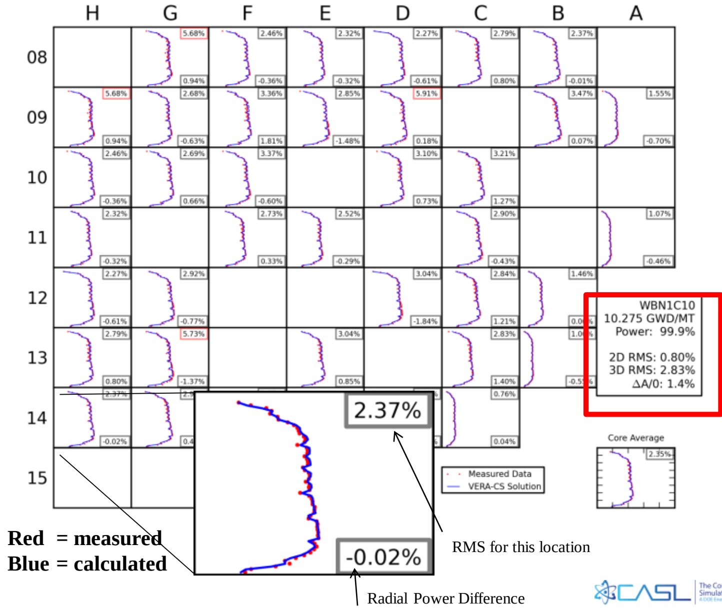
- Boron concentration required to maintain criticality due to fuel and burnable poison depletion over the fuel cycle
- BOC boron can increase due to IFBA burnup
- EOC boron typically near 0 ppm



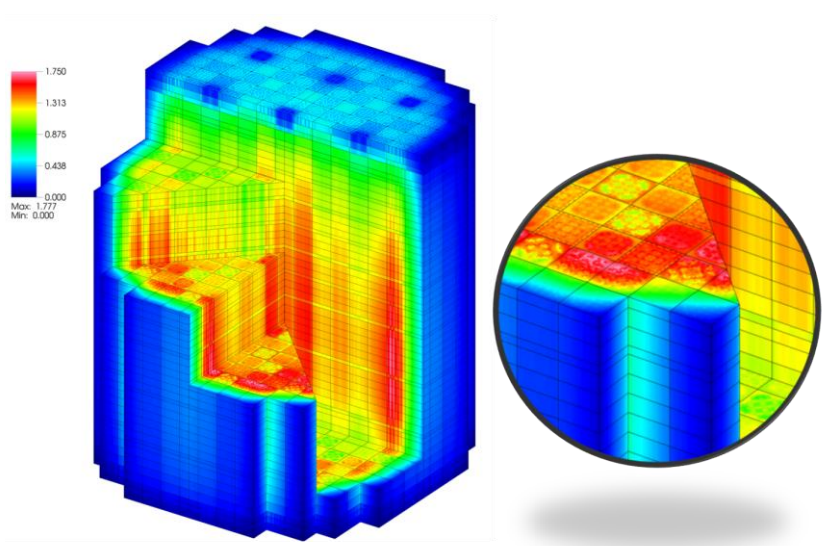
VERA-CS Calculated Critical Boron Letdown

Results represent 1.1 million core-hours

WBN1 Example Flux Map – Cycle 10

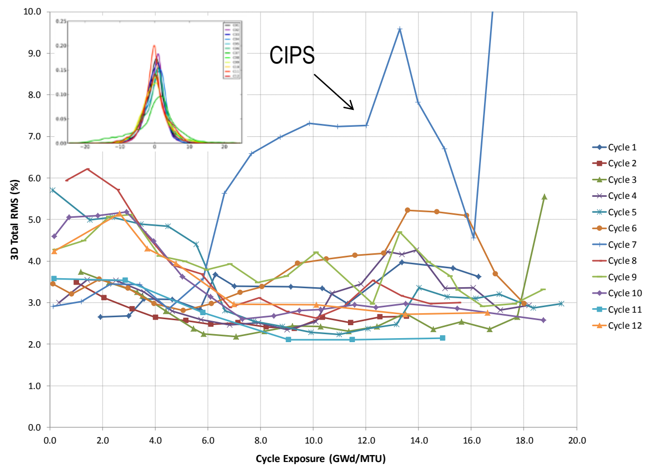


WBN1 Cycle 11 Pin Powers



WBN1 Flux Maps – 3D RMS (%)

- RMS difference between measured and calculated populations – ignoring inoperable locations
  - Includes all axial locations



- **Avg = 4.1 ± 1.1%**
- **Without Cycle 7, Avg = 3.7 ± 0.4%**
- **Acceptance criteria assumed to be < 7.5%**
- **Results are acceptable, but some outliers exist. Fairly good considering the 3D data is not available.**

July 2015

Initial Implementation of BWR Geometries in VERA-CS

Milestone FY15.CASL.006

- Purpose: Demonstrate a BWR sub region neutronics capability using a planar pin-resolved MOC methodology
- Tool: MPACT neutronics code
- Results:
  - ➢ VERA-CS can address different core configurations, with exception pin and assembly layouts must currently fall on Cartesian grid
  - ➢ Neutron cross-section library requires improvement to address BWRs likely due to hard energy spectrum

First Step into Phase 2 BWR Neutronics Capabilty

Uncertainty Quantification of VERA-CS

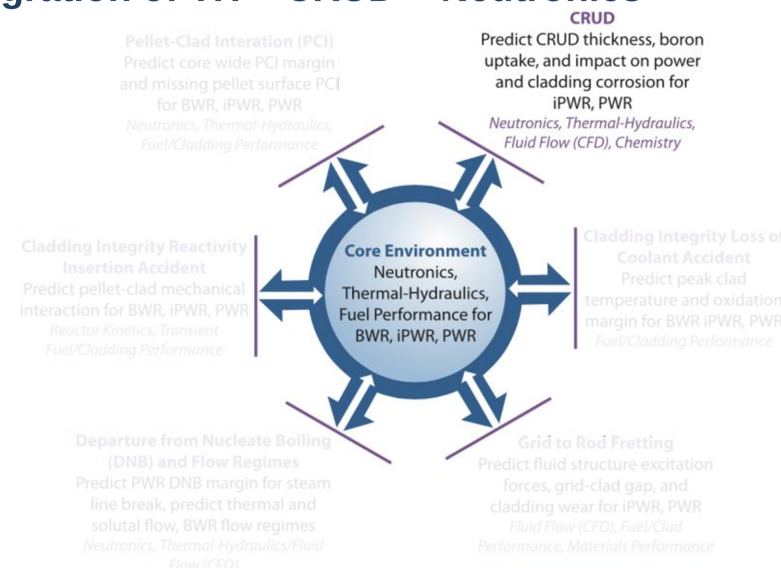
Milestone FY15.CASL.007

September 2015

- Purpose: Develop computationally realizable methodology to complete UQ for core simulation of a PWR core as a function of cycle burnup, and verify and demonstrate methodology.
- Tool: VERA-CS core simulator + ROMUSE UQ/Data Assimilation (DA) code.
- Results:
  - Applied initially to a single 3-D fuel assembly treating cross-section and thermal-hydraulic parameters uncertainties
  - Developed and applied several new UQ methodologies and verified using brute force Monte Carlo UQ method.

Already have extended UQ and DA to full core problem

Progress on CIPS Challenge Problem: Integration of TH + CRUD + Neutronics

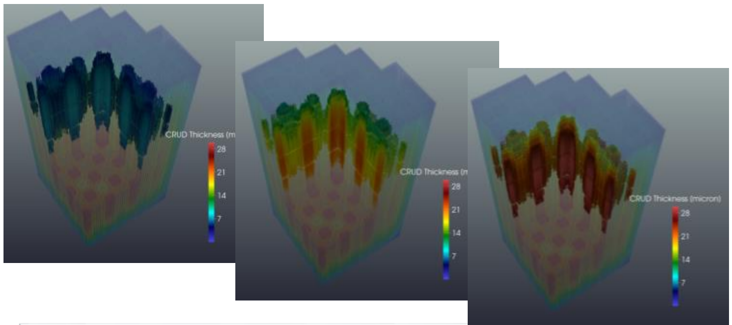


May 2015

Integration of CTF + Mamba-1D

Milestone L3.PHI.CTF.P10.02

- All CTF code modifications has been completed in FY14 with a surrogate code until Mamba-1D was available
- Initial multi-physics integration and use on a core-wide basis



First Step to Integrated CIPS Analysis Capability

May 2015

Implementation of Crud Layer Modeling in Neutronics Code

Milestone L3.PHI.VCS.P11.01

- Modifications to MPACT to incorporate CRUD layer.
- Investigation of sensitivity of modeling parameters
- Development of plan for 3-code coupling for full integration
- Identification of other requirements (restart, memory requirements etc.)

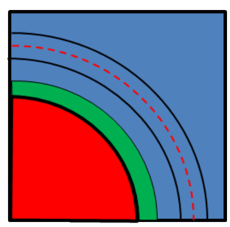


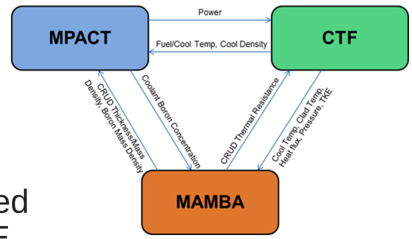
Figure 1: CRUD Regions on a Pin Cell

Integration of CTF+Mamba+Neutronics

Aug 2015

Milestone L2.PHI.P11.01

- Performed multi-physics integratoin of capabilites needed for CIPS
- Exercised capabilty for the first time and obtained first comparisons with Watts Bar Cycle 7
- Descrepancies in resutls required investigations in support of DOE reportable milestone



Application that indicated Need to Understand Integrated Coupling involving Subchannel and 1D Crud Model

Analysis of CIPS and Comparison to Plant Data

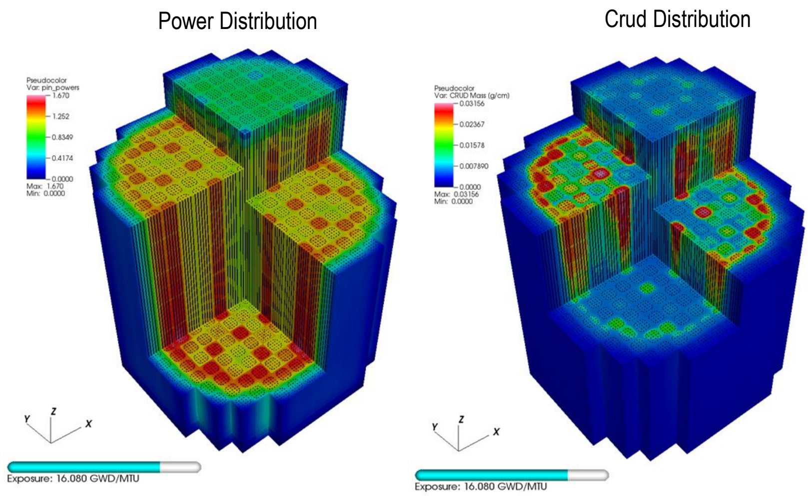
September 2015

Milestone FY15.CASL.008

- Purpose: Validate CIPS prediction capability using Watts Bar Unit 1 Cycle 7 power distribution measurements
- Tool: VERA-CS core simulator with MAMBA1D integrated into CTF
- Results:
  - By adjustment of two parameters in MAMBA1D could match measured axial offsets.
  - Robust predictive capability of MAMBA1D needs further improvement.
  - Areas for continued work identified

First Application of Integrated CIPS Capability with Comparison to Plant Data

Watts Bar 1 Cycle 7 Predicted Crud Distribution



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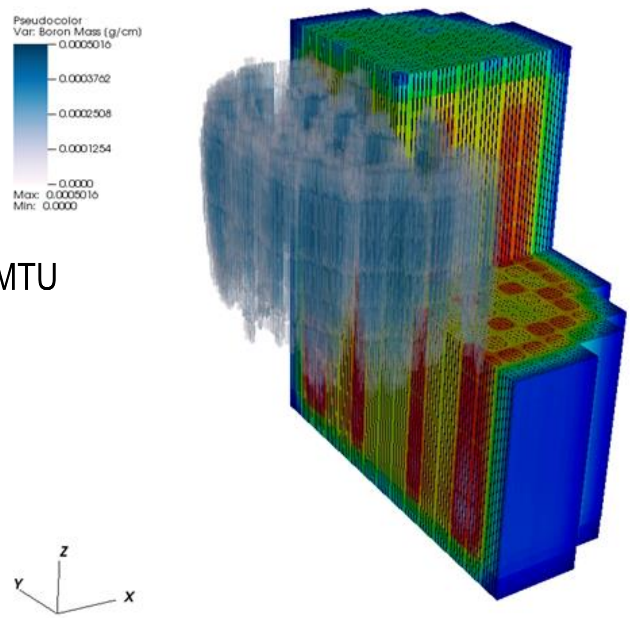
Watts Bar 1 Cycle 7 Predicted Boron Distribution

Boron Distribution at 16.08 GWD/MTU



Challenge Problem: PCMI
Milestone FY15.CASL.009

- Purpose: Validate onset of PCMI prediction capability using Braidwood Unit 1 Cycles 10 & 11 fuel performance data (suffered PCMI failures)
- Tool: BISON-CASL fuel performance code with pin-wise power distributions input using values generated by WEC core simulator.
- Results:
  - Onset of PCMI prediction capability comparable to current industry capability, implying still large gray area.
  - Number of areas where improvement is warranted were identified.

Onset of PCI still proving difficult to precisely predict

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Challenge Problem: DNB
Milestone L3:VMA.AMA.P11.02

- Purpose: For assumed steam line break accident, determine whether the low-flow (offsite power not available to power RCP) or high-flow (offsite power available to power RCP) scenario is more limiting.
- Tool: **Full core geometry** VERA-CS core simulator + STAR-CCM+ computational fluid dynamics *commercial* code.
- Results:
  - Demonstrated capability of full core geometry simulations for skewed power distribution.
  - STAR was used to determine core inlet temperature and flow distributions, with predicted flow distribution indicating larger geometry (i.e. core resistance) must be accounted for.

Further simulations required to answer question of which scenario is more DNB limiting

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Hydra-TH M-CFD Code Assessment
Milestone FY15.CASL.011

- Purpose: Document and access current status of Hydra-TH for multiphase flow capabilities.
- Tool: Hydra-TH M-CFD code
- Results:
  - Progress made but lagging what is required to support closure models development and address challenge problems
  - Hydra-TH has become open source software
  - Need to replace Hydra-TH with a CFD code that has proven capabilities to predict two-phase flow

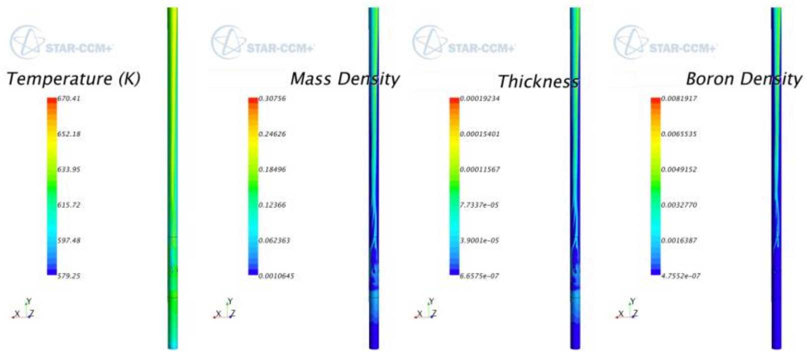
Future Development:
Production Code: STAR-CCM+
Research Code: OpenFoam

Interoperability with Commercial CFD Code
Milestone L2:PHI.P11.02

- Purpose: Develop and demonstrate the capability to integrate VERA software with non-VERA software (e.g. fuel vendor, commercial CFD or structural analysis) with either one-way or two-way coupling.
- Tool: Data Transfer Kit (DTK) + VERA + non-VERA
- Example: DTK +MAMBA1D + STAR-CCM+ (CD-adapco)
- Results:
  - Example was completed producing results that look reasonable but not rigorously verified.
  - Importance of tighter integration of CASL integrator and non-VERA software developer to achieve timely development.

This work will support CILC Challenge Problem Approach

Interoperability



Effects of swirl caused by mixing vanes is evident

Progress on Verification & Validation

- Individual V&V of codes has continued, with more emphasis on validation than verification. Codes where V&V activities have taken place include
  - MPACT radiation transport
  - CTF thermal-hydraulics subchannel
  - BISON-CASL fuel performance
  - VERA-CS core simulator
  - VERA-CS + MAMBA CIPS predictor
- FY16 milestones address either authoring or updating V&V plans for each code and several Challenge Problems and executing the plans.

FY16 work activities should result in V&V being completed in a more structured & visible manner

Advances in Fundamental Understanding

Examples of Recently Completed or Ongoing Work

- Experimentally determine the effects of CRUD on sub-cooled boiling
- ITM/DNS for high volume fraction bubbly flow regimes, machine learning for closure support
- Mechanistic Modeling of Subcooled Boiling and CHF in LWR Fuel Assemblies with Spacers
- Improve understanding Zr-O-H microscale behavior
- Initial model of uniform oxidation kinetics using Hognose

In addition, development of mathematical algorithms is progressing

FY16 DOE-Reportable Milestones

Milestone ID	Milestone Description	Finish Date
FY16.CASL.001	Develop and test subchannel thermal hydraulics to support modeling of BWR operating conditions	January 2016
FY16.CASL.002	Demonstrate Uncertainty Quantification and Data Assimilation for Watts Bar Unit 1 Cycle 1	March 2016
FY16.CASL.003	Identify fuel performance capabilities needed for analysis of Reactivity Insertion Accidents (RIA) and complete initial implementation	May 2016
FY16.CASL.004	Initiate VERA working group by holding first meeting	April 2016
FY16.CASL.005	Complete VERA integrated Verification and Validation (V&V) requirements and planning and update V&V manuals for individual codes	June 2016
FY16.CASL.006	Define post CASL sustainability strategy	July 2016
FY16.CASL.007	Demonstrate VERA Core Simulator performance improvements	August 2016
FY16.CASL.008	Implement VERA transient capability with internal heat conduction feedback for PWRs for analysis of Reactivity Insertion Accidents (RIA)	September 2016
FY16.CASL.009	Demonstrate DNB analysis methods using CFD for Non-Mixing Vane and V5H grid spacers	September 2016
FY16.CASL.010	Assess the analysis capability for core-wide PWR Pellet-Clad Interaction (PCI) screening and demonstrate detailed 3-D analysis on selected subregion	September 2016
FY16.CASL.011	Qualify CFD-based PWR Crud Induced Localized Corrosion (CILC) capability to identify high-risk fuel rods	September 2016

Deployment and Outreach

- First Quick Start Training Workshops held at ANFM and the Summer Student Workhop
- Release process is maturing with updated VERA releases, the first VERA-EDU release
- ANS Young Members Group Webinar
- Numerious papers, panel particpation, keynote talks at Conferences (ANFM, M&C2015, NURETH, to name a few)
- Updated website, technotes
- July seminar at NEI and information exchange meeting the NRC

Establishment of VERA Working Group Planned for FY16

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CASL Director Testifies on Hubs to House Science, Space and Technology Energy Subcommittee

- June 17, 2015 oversight to support authorization of Hubs
  - H.R. 1870 introduce by Rep Grayson and incorporated into H.R. 1868 Reauthorizing the American Competes Act
- Questions posed in hearing invitation:
  - What are the primary research and development goals of CASL? Since the hub was organized by DOE, what progress has been made towards those goals?
  - How does the integrated research model employed at the hubs advance research goals within the Office of Science and applied energy programs at DOE?
  - How does the private sector interact with CASL? In what way does CASL prioritize technology transfer of technologies developed at the hub?

Congress of the United States
House of Representatives
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

June 9, 2015

Dr. Jess Gehin
Director
Consortium for Advanced Simulation of Light Water Reactors (CASL)
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

Dear Dr. Gehin:

The Committee on Science, Space, and Technology Subcommittee on Energy of the U.S. House of Representatives will hold a hearing to provide oversight of the Department of Energy (DOE) Innovation Hubs on Wednesday, June 17, 2015 at 10:30 a.m. in room 2318 of the Rayburn House Office Building. I would like to request your presence to testify on behalf of the Consortium for Advanced Simulation of Light Water Reactors (CASL) at this hearing.

The purpose of this hearing is to provide an update to the Committee on the progress of the research and development conducted through the Energy Innovation Hubs, and describe areas where the integrated research approach has accelerated the achievement of Department of Energy scientific research goals.

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Annual Stakeholder Report Developed to Support DOE Review

- **The FY 15 annual stakeholder report was submitted to DOE on October 16**
  - All of the references cited in the report and all of the FY 2015 DOE Reportable Milestone Documents were also submitted.
- **The DOE review team has reviewed this submission and provided additional questions**
- **A half-day review meeting is scheduled for the morning of November 12 in Washington DC**
  - The meeting will be held at the Wardman Park Marriott to coordinate with the ANS Winter Meeting
- **A DOE review report should be ready by November 30**

New review process is going well so far….

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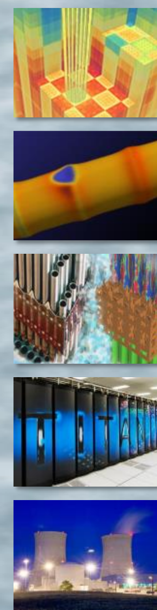
www.casl.gov

VERA-CS: Performance and Validation

Physics Integration (PHI)
Radiation Transport Methods (RTM)

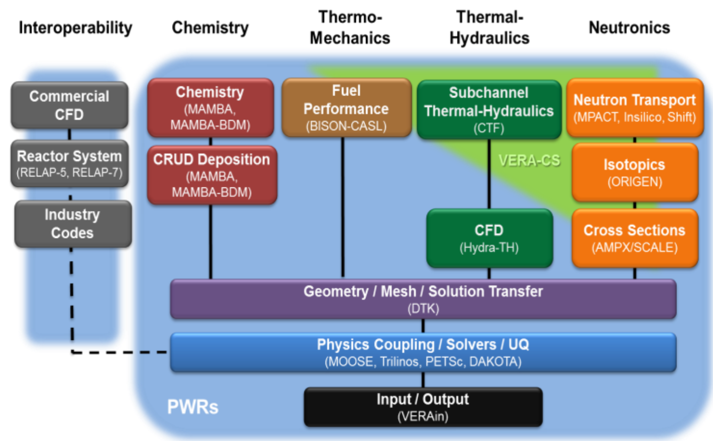


Overview

- VERA-CS Summary
- Core Physics Benchmark Progression Problems
- SMR Demonstration
- BEAVRS Cycle 1 Benchmark
- Krško Cycle 1
- Watts Bar Nuclear 1 Benchmark
- Future Applications
- Development Needs

- Not covered:
  - Anything other than VERA-CS
  - AP1000 Results (see IC presentation tomorrow)
  - Validation against B&W Criticals
  - SLB efforts (Sung, L3:VMA.AMA.P11.01)

Virtual Environment for Reactor Applications

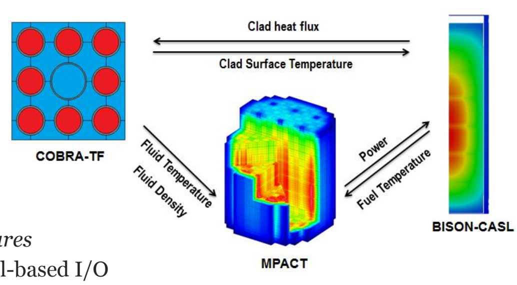


VERA is the “Environment”

VERA-CS

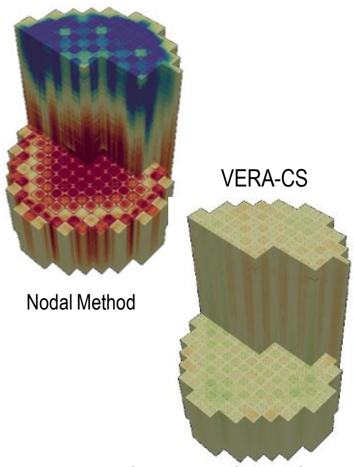
- Coupled VERA components for virtual reactor core simulation
  - Steady-state fuel cycle depletion and reload/shuffling
  - Operational maneuvers (load follow, power changes)
- Provides boundary conditions, power histories, isotopics, etc. for Challenge Problems

- Currently Includes:
  - **MPACT** – 3D neutron transport
  - **CTF** – subchannel T/H
  - **ORIGEN** – Isotopic depletion and decay
  - ***Bison-CASL*** – *Fuel temperatures*
  - **VERAIn** – User friendly, model-based I/O



Industry Methods vs. VERA-CS

- 2D infinite lattice physics in many energy groups
- Macroscopic cross section homogenization and parameterization
- 3D nodal diffusion in few energy groups
- Node average T/H quantities for feedback and depletion
- Pin power reconstruction
- Pin exposure reconstruction
- Spectral history corrections
- Approximate reflector models
- Fast runtime



Fission Rate Distributions Comparisons to CE Monte Carlo

- Whole-core 3D transport
- 47 energy groups
- Explicit pin-by-pin powers with intra-pin distributions
- Explicit pin-by-pin depletion at local spectrum
- Explicit channel-by-channel two-phase T/H with cross-flow
- *Simple pin-by-pin fuel temperatures by table-lookup*
- Semi-explicit 3D reflector geometry
- Runs on 1000's of cores over hours or days

VERA-CS is built for Accuracy at the Fuel Rod Level

Core Physics Progression Problems

- Created May 2011 for application-based development and testing
- ~75 CE Monte Carlo (KENO-VI) reference solutions for Problems 1-5
- Measured data for Problems 5, 9, & 10
- Specifications and solutions publicly available
- Revision 4 released 8/2014
- Problems 1-10 <u>completed</u> and <u>solved</u> with VERA-CS in 2015
  - MPACT +CTF+ORIGEN
  - 47g ENDF/B-VII.0 cross sections with TCP0
  - Fuel temperatures from 'arbitrary' CTF gap conductance

Progression Problem Summary

- #1 2D HZP Pin Cell ✓
- #2 2D HZP Lattice ✓
- #3 3D HZP Assembly ✓
- #4 HZP 3x3 Assembly CRD Worth ✓
- **#5 Physical Reactor Zero Power Physics Tests (ZPPT)** ✓
- #6 HFP BOL Assembly ✓
- #7 HFP BOC Physical Reactor w/ Xenon ✓
- **#8 Physical Reactor Startup Flux Maps** ✓
- **#9 Physical Reactor Depletion** ✓
- #10 Physical Reactor Refueling ✓

(2014 Mtg)

Hot-Zero-Power isothermal calcs w/o T/H feedback

CE MC references

At operating conditions with T/H feedback

No reference solutions but some plant data

*Bold indicates availability of measured reactor data

Progression Problems

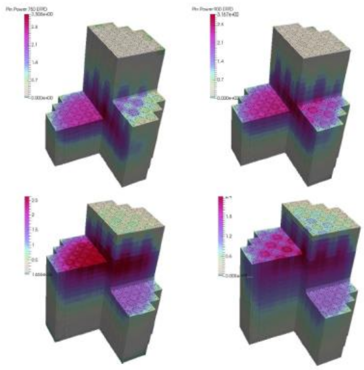
- Problem 7 Results presented at this meeting last year
- Problems 8-10 completed in FY2015

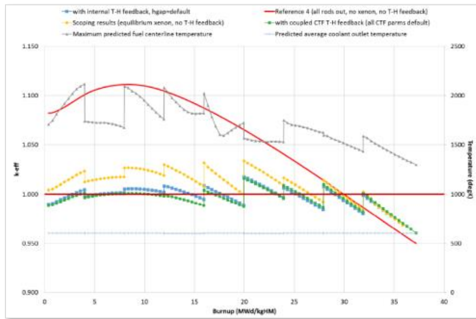
- Progression Problems concluded with
  Watts Bar Benchmark!

SMR Demonstration

Montgomery, L1:CASL.P10.01, Feb. 2015

- SMR calculations performed to demonstrate applicability to Small Modular Reactor design
- Calculation of excess reactivity, cycle length, and peaking factors
- Illustrated the capabilities of VERA-CS to develop a control component management strategy
  - Multiple control rod banks / Multiple cycle depletions
  - No reference solutions



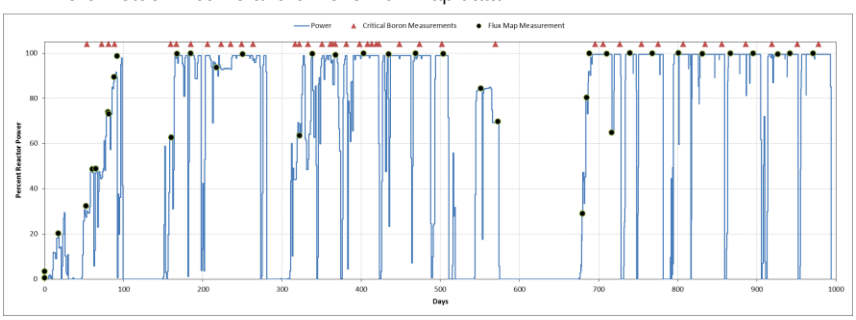


Up to 3815 cores

BEAVRS Benchmark

Collins, L2:PHI.P10.01, March 2015

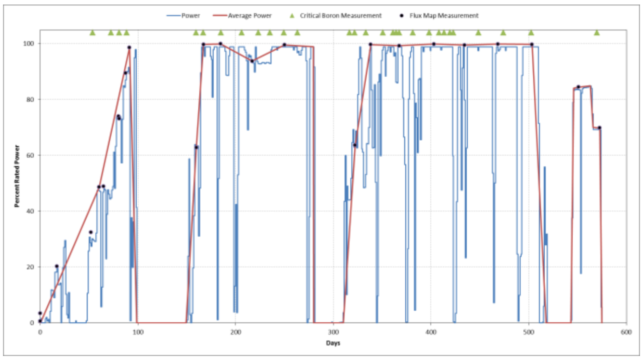
- Benchmark for Evaluation and Validation of Reactor Simulations (MIT)
- Provides 2 cycles of data
  - Detailed assembly designs and core loading
  - Daily power history; no rod positions
  - Zero Power Physics Test (ZPPT) results
  - Boron letdown curve and 61 level flux map data



N. Horelik, B. Herman, B. Forget, and K. Smith. Benchmark for Evaluation and Validation of Reactor Simulations (BEAVRS), v1.0.1. *Proc. Int. Conf. Mathematics and Computational Methods Applied to Nuc. Sci. & Eng.*, 2013. Sun Valley, Idaho

BEAVRS Cycle 1 Model

- Cycle 1 Power history very difficult to model
  - Capacity factor - 57%
- Approximate power history is developed
  - Attempt to capture major features of operating history
  - Get data points close to flux map measurements



BEAVRS Cycle 1 Zero Power Physics Tests

- Critical positions

	K-eff	Difference [pcm]
ARO	0.99819	-181
D In	0.99972	-28
C/D In	0.99913	-87
A/B/C/D In	0.99769	-231
SE/SD/SC/A/B/C/D in	0.99660	-340

ITC [pcm/ºF]

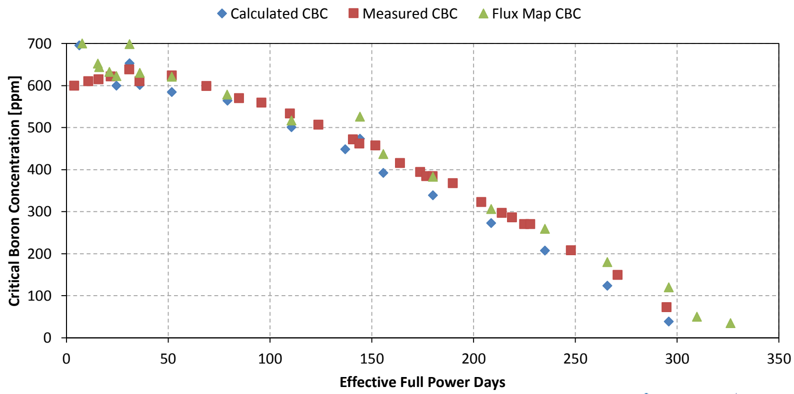
Calculated	Measured
-2.09	-1.75
-3.47	-2.75
-8.34	-8.01

- Control Rod Worth Measurements

	Calculated	Measured	Difference
D	780	788	-1.1%
C with D In	1252	1203	4.1%
B with C/D In	1175	1171	0.3%
A with B/C/D In	568	548	3.6%
SC with A/B/C/D In	477	461	3.5%
SD with SC/A/B/C/D In	765	772	-1.0%
SE with SD/SC/A/B/C/D In	1071	1099	-2.5%

BEAVRS Cycle 1 Critical Boron Letdown

- Cycle 1 is simulated with simplified power history, control rods fully withdrawn, and equilibrium xenon
- VERA-CS under predicts boron throughout cycle
  - Maximum difference – 52 ppm
  - Average Difference – 27 ppm

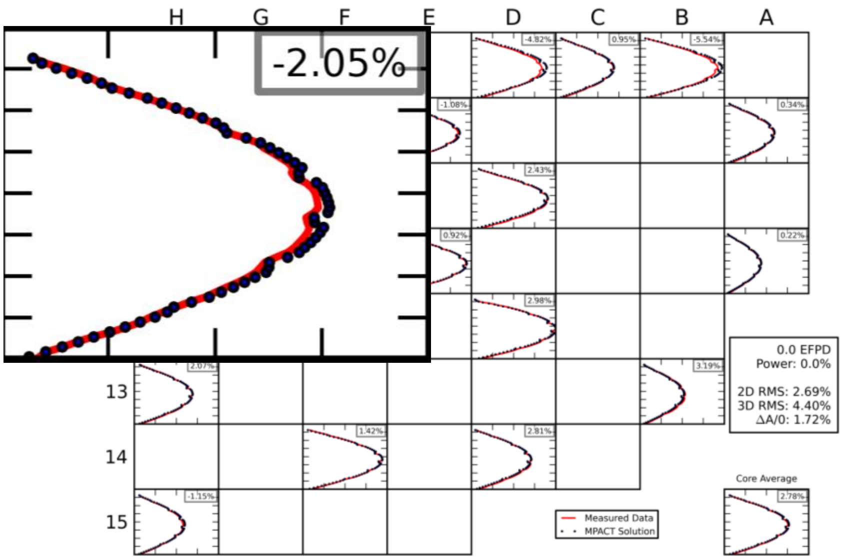


*No basis for fuel temperatures – single gap conductance set in CTF

BEAVRS Cycle 1 Flux Maps

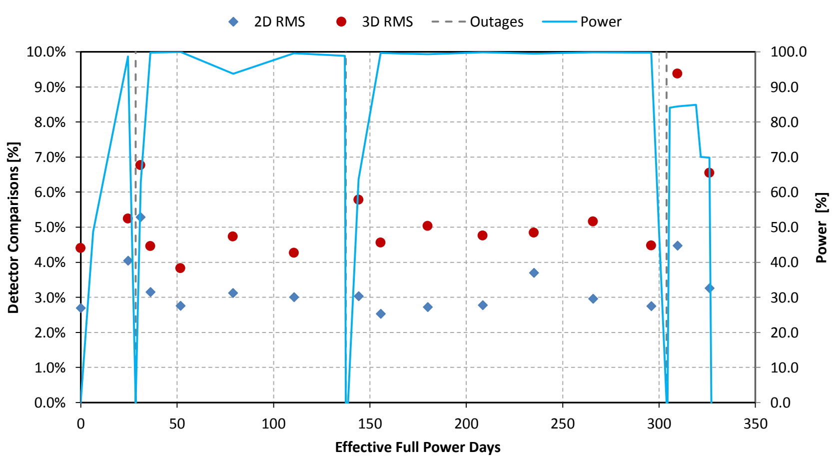
- MPACT extracts detector signal using local flux in the detector thimble with the fission cross-section for ^{235}U
- Detector signals are normalized and saved for post processing
- Detector data is fit using a cubic spline and mapped onto 61 equal spaced levels for comparison with measured data
- A script performs this mapping and compares local and integral comparisons
  - 3D RMS of detector signal
  - Axially integrated RMS of detector signal
  - Measured vs Predicted Axial Offset from detector signals

BEAVRS Cycle 1 Zero Power Flux map



BEAVRS Cycle 1 Flux Map Comparisons

- Average 2D RMS – 3.0%
- Average 3D RMS – 4.8%

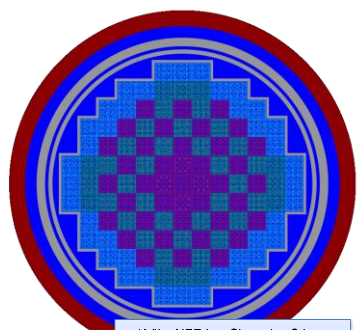


BEAVRS Cycle 2

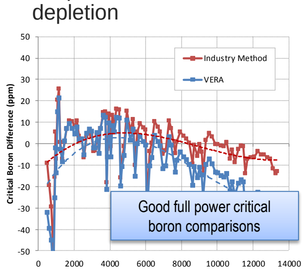
- BEAVRS Cycle 2 Model to be developed in
  - Milestone L3:PHI.VCS.P12.04
  - Lead: Ben Collins
  - Due: 05/30/2016

Krško NPP Cycle 1

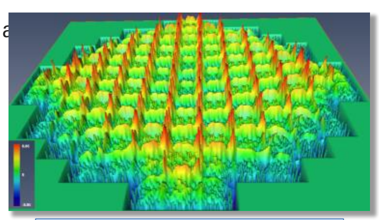
- Collaboration between ORNL, Westinghouse, and the Jožef Stefan Institute (JSI) of Slovenia
- Measured data provided by JSI and Krško for benchmarking
  - Zero Power Physics Tests results
  - Critical boron concentrations
  - Measured radial power distributions over the entire cycle
- Results from currently licensed industrial methods also provided for comparison
- Required 8496 cores and 21 hours for the full core depletion



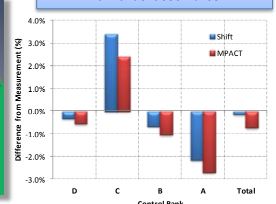
Krško NPP is a Slovenian 2-loop pressurized water reactor with 121 16x16 fuel assemblies



Good full power critical boron comparisons



Fuel rod power comparisons to industrial methods demonstrates the value of VERA



Excellent control rod reactivity worth comparisons

CASL is broadening the validation bases for VERA

Watts Bar Multi-Cycle Benchmark

Godfrey, L1.CASL.P11.02, June 2015

Cycles 1-12

- Level 1 DOE-Reportable milestone completed June 30
  - CASL-U-2015-0206-000
- Scope: Multiple fuel cycles of Watts Bar Nuclear 1
- Components:
  - MPACT (Collins, Kochunas, Jabaay, Stimpson)
  - CTF (Salko)
  - ORIGEN (Wieselquist)
  - Bison-CASL (Powers, Capps, Montgomery)
  - VERAIn (Simunovic)
  - Cross sections (Kim)
  - Analysis (Godfrey, Collins)
- Data
  - Fuel specifications (Secker)
  - Reactor specifications (Montgomery)
  - TPBAR specifications (Montgomery)
  - Operating history (Montgomery)
  - Measured data (Montgomery)
- Benchmark Results
  - HZP critical boron concentrations
  - HZP Control bank worths
  - HZP Isothermal temperature coefficients
  - HFP critical boron letdown
  - HFP flux maps

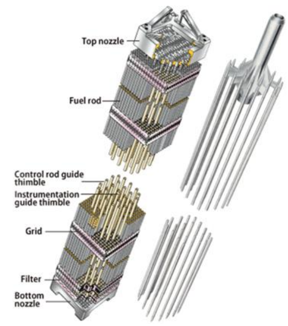
Huge Accomplishment by a Fantastic Team!

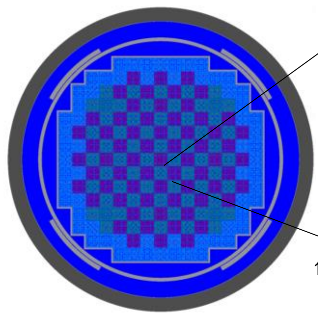
Watts Bar Nuclear Plant – Unit 1

- Operated by Tennessee Valley Authority in Spring City, TN
- Traditional four-loop Westinghouse PWR
- Began operation in 1996
- Currently in 13th fuel cycle
- 3411 MW_{th} initial rated thermal power
  - Uprated to 3459 MW_{th} in Cycle 4
- 144.7 Mlbm/hr rated flow
- Typical inlet conditions = 557 °F @ 2250 psi
- Unit 2 Startup in 2016

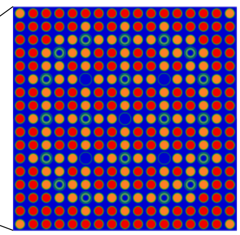
WBN1 Core Designs

- 193 Westinghouse 17x17 fuel assemblies
  - 50,952 fuel rods with 12' active fuel height
- Typical 3-batch "ring-0f-fire" designs
- ~18 month fuel cycle lengths
- IFBA/WABA burnable poisons
- Tritium-producing burnable absorber rods (TPBARs) starting in Cycle 6
- Soluble boron for excess reactivity control





Radial Slice through WBN1 Reactor Vessel



17x17 Assembly Layout with IFBA and WABA

IFBA is <10 μm coating on the fuel pellet

WBN1 Control Banks & Detectors

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1															
2				SA		B		C		B		SA			
3					SD		SB		SB		SC				
4		SA		D				D				D		SA	
5			SC		A						A		SD		
6		B				C		A		C				B	
7			SB										SB		
8		C		D		A		D		A		D		C	
9			SB										SB		
10		B				C		A		C				B	
11			SD		A						A		SC		
12		SA		D				D				D		SA	
13					SC		SB		SB		SD				
14				SA		B		C		B		SA			
15															

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1							D			D					
2			D			D		D							
3								D		D		D		D	
4		D	D					D							
5					D				D		D		D		
6	D		D			D		D						D	
7				D			D			D			D		
8	D		D		D		D			D		D	D	D	
9		D							D		D				D
10					D		D					D			
11	D				D			D			D				D
12						D			D			D			
13			D		D			D						D	
14			D				D			D		D			
15					D			D							

- 57 control assemblies each with 24 hybrid B_4C/AIC rodlets
- Grouped into 8 banks; 4 safety and 4 control
- Move in/out of fuel in 0.625" steps (~230 max)
- 58 in-core moveable detectors

Simulation Process

- Core and fuel models built with VERAIn from specifications provided by TVA and Westinghouse for Cycles 1 through 12
- All input created, modified, and executed on INL's Falcon using 4307 cores (180 nodes)

1. Each cycle's fuel was shuffled from the previous cycle(s) and decayed for the outage time (except Cycle 1 of course)
   - BOC restart file written
2. Zero Power Physics Tests (ZPPT) parameters calculated
   1. Initial ARO critical boron concentration
   2. Control bank reactivity worths
   3. Isothermal temperature coefficient
3. HFP reactor core depletion performed with boron search at average conditions over each cycle, with depletion steps corresponding to points with measured data
   - EOC restart file written
4. Output HDF5 files transferred to local clusters for post-processing
   1. Critical boron letdown comparisons
   2. HFP Flux Maps

~10,000 core-hours

~15,000 core-hours

~90,000 core-hours

~115,000 core-hours per fuel cycle

Model Description and Details

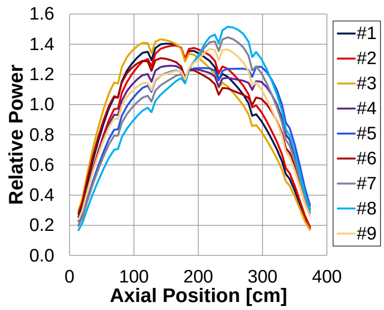
- Quarter-core rotational symmetry used to reduce the computational requirements
- Axial meshing chosen to match fuel and poison boundaries and spacer grid locations
- <≈3" axial planes in the fuel
  - Cycle 1: 55 planes (4015 cores)
  - Cycle 2+: 59 planes (4307 cores)
- Baffle-only radial reflector
- Instrument thimbles removed from depletions
- Equilibrium xenon for cycles 2+
- Spatial decomposition
  - 59 planes x 73 assemblies = 4307 mpi processes
- New hybrid SP_3 nodal method
- New control rod cusping model
- New Bison-CASL fuel temperature tables
- New ORIGEN library

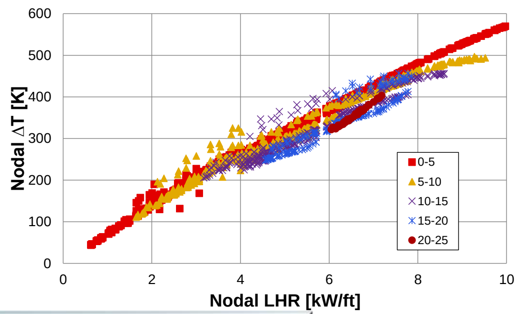
Many new features have improved the accuracy, speed, and stability of VERA-CS

Fuel Temperatures from Bison-CASL

Powers, Capps, Montgomery

- Bison-CASL 2D R-Z model of WBN1 Cycle 1 fuel rod used to calculate volume-averaged fuel temperatures
- Nine power histories calculated from VERA-CS to provide bounding power histories and axial shapes
  - Three power levels x Three axial offsets (core average)
- Bison-CASL results extracted and processed into tables of fuel temperature vs. LHR and exposure





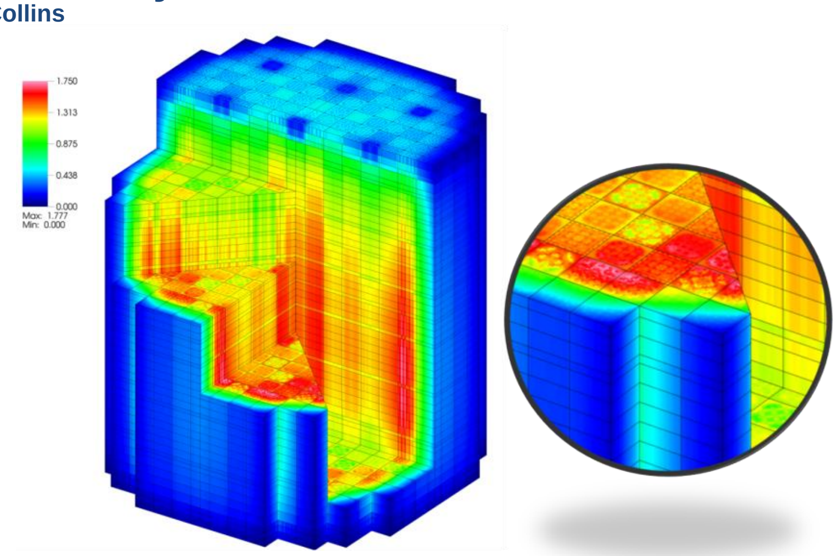
Just a first cut.. More effort is needed.

Notable Achievements with VERA-CS

- VERA-CS successfully performed all calculations for first 12 fuel cycles of WBN1
  - First time in CASL performing anything beyond Cycle 1
- Fastest turnaround time ever obtained
  - Falcon is fast and generally was available to CASL
  - Fuel temperature tables reduced the CTF runtime
  - Axial reflector regions optimized
  - MoC ray spacing not reduced for IFBA (small bias at BOC)
- Most accurate results ever obtained
  - Used proprietary reactor and fuel design specifications and materials
  - 47-group transport-corrected P0 cross sections
  - First use of Bison-CASL with VERA-CS (uncoupled)
  - First time comparing measured flux map results with detailed history, models
- Most reliable/stable executions ever performed
  - New hybrid SP_3 option
  - Reduced axial reflector regions
  - Depletions include 4899 neutronics/TH iterations with no convergence issues

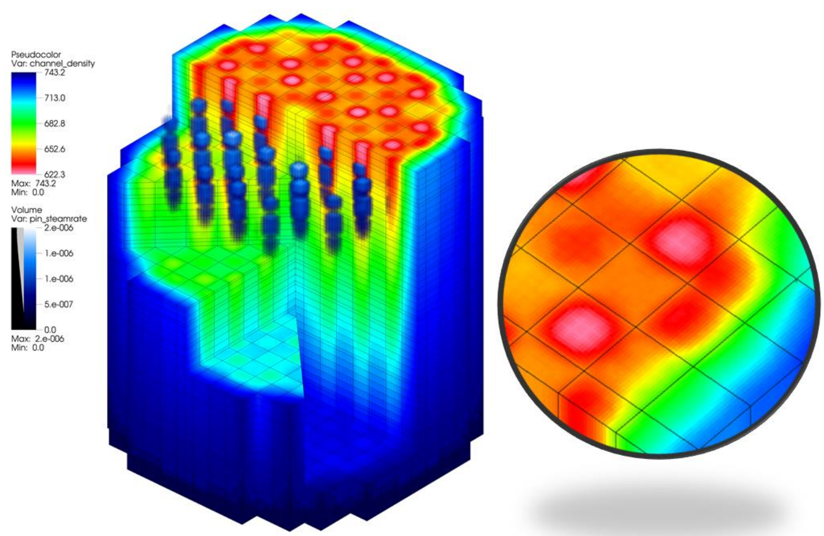
VERA-CS is the highest fidelity PWR reactor core simulator available

WBN1 Cycle 11 Pin Powers
Collins



Unprecedented Fidelity

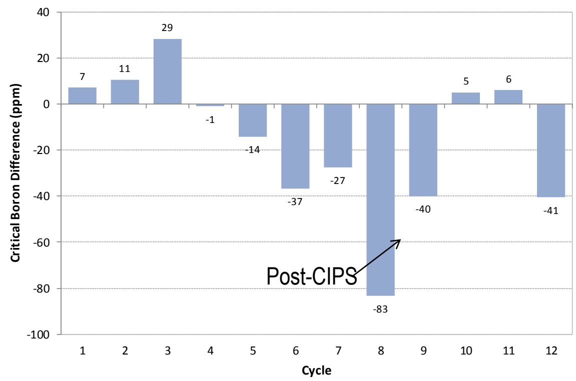
WBN1 Cycle 11 Coolant Density
Collins



Unprecedented Fidelity

BOC HZP Boron Endpoint (ARO)

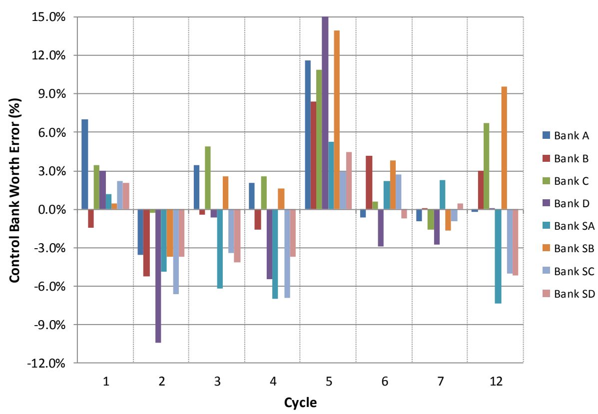
- Initial criticality measurement for each cycle
  - Subsequent to fuel reload and shuffling
  - Isothermal conditions and without T/H feedback
- Reactivity error gauged by difference in concentration (ppm) of soluble boron



- **Avg = -15 ± 31 ppm**
- **Without Cycle 8 (CIPS), Avg = -9 ± 24 ppm**
- **Acceptance criteria typically < 50 ppm**
- **Mean is ok, but variance is higher than preferred**

BOC HZP Control Bank Worths

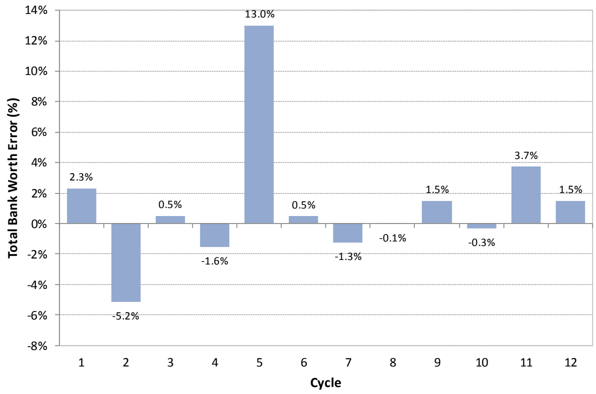
- ZPPT measurements at the beginning of each cycle
  - Isothermal conditions without T/H feedback
- Cycles 8-11 didn't measure the individual banks
- Comparison is calculated as a relative error in reactivity worth



- **Avg = 0.7 ± 3.9%**
- **Abs Avg = 4.1%**
- **Acceptance criteria typically < 15%**
- **Results are good, but there are clear outliers. Cycle 5 data needs further investigation**

BOC HZP Control Bank Worths

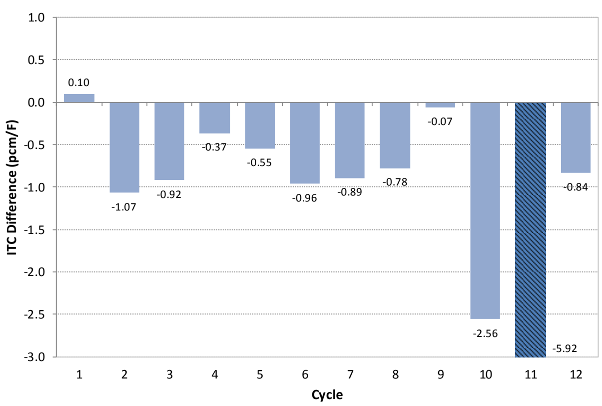
- ZPPT measurements at the beginning of each cycle
  - Isothermal conditions without T/H feedback
- Total worth is sum of all banks



- **Avg = 1.2 ± 4.3%**
- **Without Cycle 5, Avg = 0.1 ± 2.3%**
- **Acceptance criteria typically < 10%**
- **Results are very good. Cycle 5 data needs further investigation**

BOC HZP Isothermal Temperature Coefficient

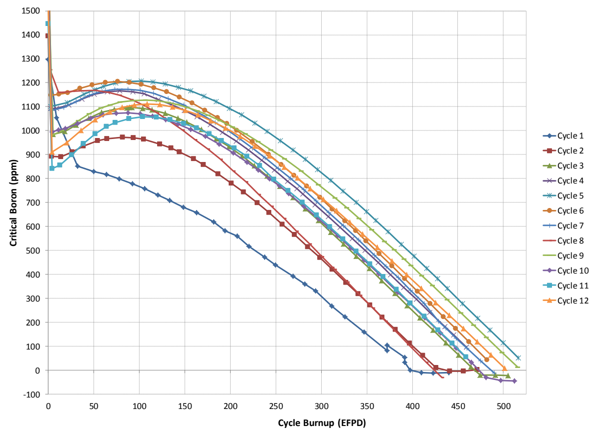
- Part of ZPPT measurements at the beginning of each cycle
  - Isothermal conditions without T/H feedback
  - ~< 5 °F perturbations in system temperature
- Comparison is absolute difference in reactivity coefficients



- **Avg = -0.8± 0.7 pcm/°F**
- **Cycle 11 measurements are suspect**
- **Acceptance criteria typically < 2 pcm/°F**
- **Negative bias but acceptable**

WBN1 HFP Boron Letdown

- Boron concentration required to maintain criticality due to fuel and burnable poison depletion over the fuel cycle
- BOC boron can increase due to IFBA burnup
- EOC boron typically near 0 ppm



VERA-CS Calculated Critical Boron Letdown

Results represent 1.1 million core-hours

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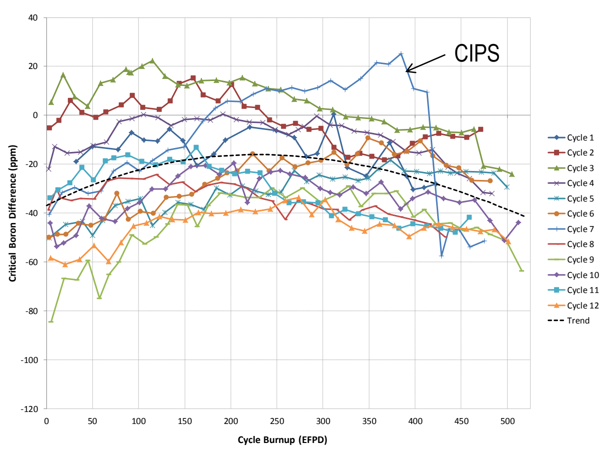
HFP Boron Letdown Differences

- Differences vary depending on ^{10}B fraction in coolant, which can be significantly depleted over a fuel cycle (worth up to -80 ppm)
- Few measurements of ^{10}B were available for older cycles, so some engineering "guestimation" was required, esp. for Cycles 1-3.



- **Avg = -23 ± 20 ppm**
- **Without Cycles 1-3 (no ^{10}B data) and 7 (CIPS), Avg = -32 ± 15 ppm**
- **Acceptance criteria typically < 50 ppm**
- **Clear negative bias with small exposure dependency. Needs more research.**

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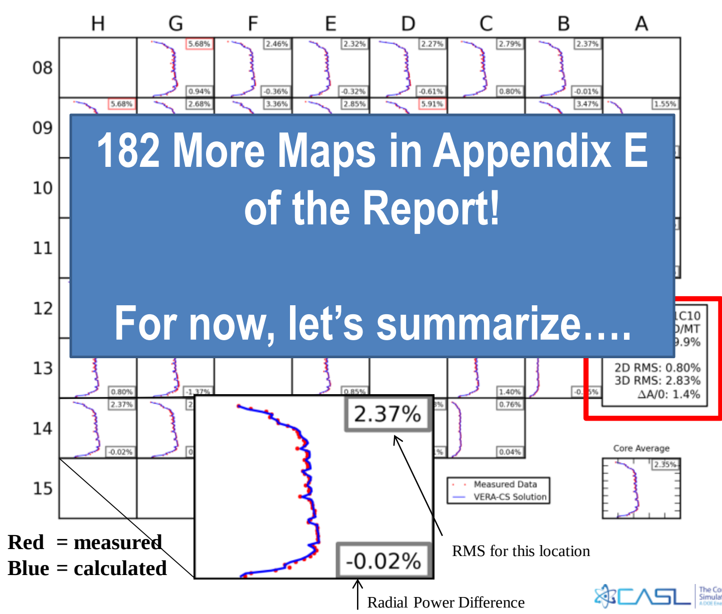
Core Power Distributions

- In-core instrument responses are measured ~monthly (termed ‘flux maps’)
  - 610 levels measured initially, and collapsed to 61 levels for analysis
- VERA-CS calculates the instrument response in each instrument tube (every location in quarter-core)
- The measured responses were collapsed to quarter-core locations and each distribution is normalized, ignoring locations indicated as inoperable
- Results are provided as Root-Mean-Square differences of the distributions (%)
- Cycle 4-12 measured data is missing 3D results, but they have been “reconstructed” from raw signals
  - i.e. probably not as accurate as we would like
- 183 flux maps selected for comparison

WBN1 Example Flux Map – Cycle 10

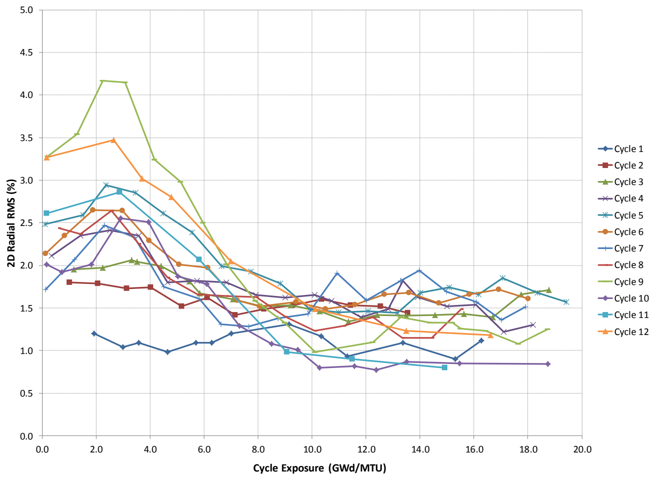


182 More Maps in Appendix E of the Report!

For now, let’s summarize….

WBN1 Flux Maps – 2D RMS (%)

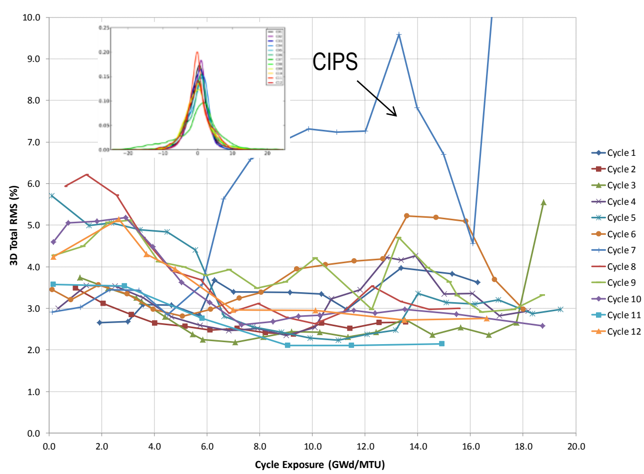
- RMS difference between populations of axially-integrated values (radial distributions)



- **Avg = 1.9 ± 0.3%**
- **Acceptance criteria typically < 5%**
- **Results are good in the latter half of each cycle, but outliers exists in the first half of some cycles**

WBN1 Flux Maps – 3D RMS (%)

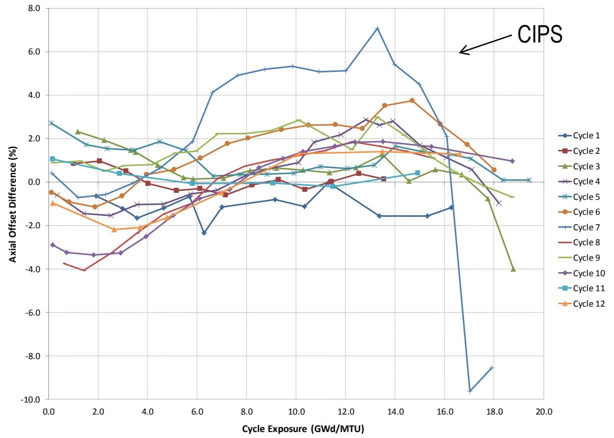
- RMS difference between measured and calculated populations – ignoring inoperable locations
  - Includes all axial locations



- **Avg = 4.1 ± 1.1%**
- **Without Cycle 7, Avg = 3.7 ± 0.4%**
- **Acceptance criteria assumed to be < 7.5%**
- **Results are acceptable, but some outliers exist. Fairly good considering the 3D data is not available.**

WBN1 Flux Maps – Axial Offset (%)

- Axial Offset represents the axial power shape in the reactor core
  - Expressed as power difference between the top and bottom of the core as a fraction of total power
- Comparison is the absolute difference between measured and calculated instrument AOs



- **Without Cycle 7, Avg = 0.3 ± 0.8%**
- **Acceptance criteria assumed to be < ± 3%**
- **Results are good, with larger errors earlier in the cycles (consistent with power dist. differences)**

WBN1 Flux Maps Summary (%)

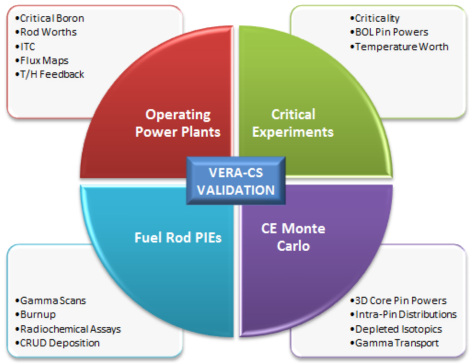
Cycle	Count	ΔAO	1D RMS	2D RMS	3D RMS	2D Max	Det Max	3D Max
1	13	-1.17	2.55	1.10	3.29	3.37	7.25	27.28
2	13	0.08	1.11	1.60	2.70	3.99	7.29	31.79
3	19	0.45	1.87	1.67	2.92	5.95	8.34	42.03
4	19	0.52	2.14	1.77	3.23	4.82	8.37	40.74
5	19	1.04	2.33	2.05	3.64	8.02	9.61	38.74
6	18	1.38	2.60	1.92	3.77	6.15	9.60	41.77
7	18	1.79	5.17	1.74	6.73	5.94	15.70	33.31
8	15	-0.35	3.03	1.77	4.00	7.67	10.27	43.63
9	19	1.32	2.41	2.35	3.94	10.03	11.88	41.72
10	16	-0.43	2.79	1.56	3.64	7.55	9.62	38.15
11	6	0.25	1.52	1.88	2.77	7.36	7.85	21.51
12	8	-0.43	2.23	2.47	3.72	11.54	12.32	37.15
Total	183	0.50	2.75	1.95	4.08	11.54	15.70	43.63
St. Dev.		0.85	0.98	0.32	1.05			

Future VERA-CS PWR Applications

- Future applications of VERA-CS driven by VERA-CS Validation Plan (CASL-U-2014-0185-000)
  - Additional reactor types (3-loop, 2-loop, B&W, CE, etc.)
  - Additional fuel types (16x16, 15x15, MOX, etc.)
  - Additional burnable poison types (B_4C-Al_4O_3, gadolinia)
  - Gray control rods
  - Fixed in-core detectors

Where are we going to run all of these?

- Four-part plan to get a wide range of coverage
  - More power plant benchmarks
  - Critical experiments
  - Comparison to post-irradiation exam data
  - Comparisons to detailed CE Monte Carlo reference solutions



Collaboration with External Stakeholders is Required

L3:PHI.VCS.P9.04

VERA-CS PWR Development Needs

- Thermal expansion
- Gamma transport
- Fuel temperature input/feedback from Bison-CASL
- Axial re-meshing for fuel type transitions
- Support for multiple fuel rods and guide tube types in CTF input pre-processor
- Further improvement in runtime performance
  - 1000 core goal within reach
- Gadolinia depletion qualification
- Fixed in-core detector models
- Control rod depletion
- Ex-core detector models
- Vessel fluence capability
- Improved Input/Output
- And more…

Impressive capability, but more is needed!

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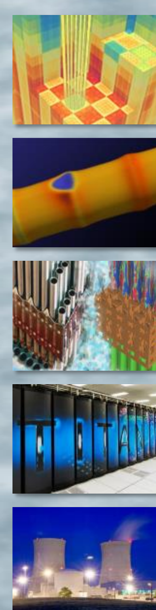
VMA Spotlight: UQ and Data Assimilation Activities

Ralph Smith – North Carolina State University

Separate attached pdf file of presentation



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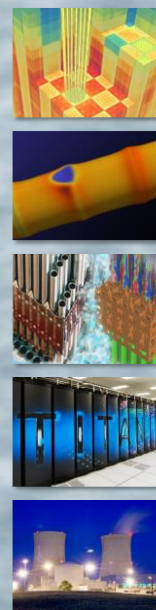
U.S. DEPARTMENT OF ENERGY

CASL VERA Market Analysis Update

Rafael Estevez, Sarah Edge
CASL TDO Workshop
11/3/2016



The Consortium for Advanced Simulation of LWRs
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U.S. DEPARTMENT OF ENERGY

Agenda

- Introduction to the NCSU TEC Process
  Rafael Estevez
- Market Analysis Goals and Project Status Review
  Sarah Edge
- Questions

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Rafael Estevez

CASL Market Analysis Team Member
Accelerating Commercialization of Technologies

NCSU Poole College of Management MBA Student
HiTEC Scholar

Email: rcesteve@ncsu.edu
Phone: 919-621-0902

NC STATE UNIVERSITY POOLE COLLEGE OF MANAGEMENT TEC
Technology Entrepreneurship & Commercialization

Developing the next generation of Entrepreneurs and the High Growth companies of tomorrow.

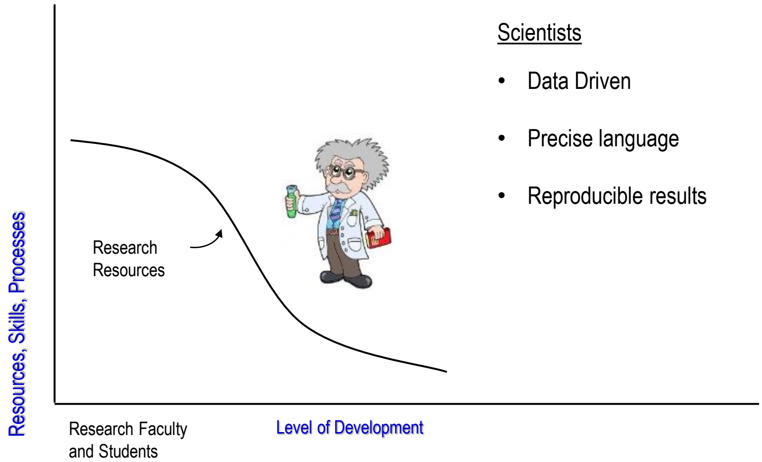
Crossing the Valley of Death

Technology Commercialization in Today's University

Invention / Innovation

- **Invention** - the formulation of new ideas for products or processes
- **Innovation** - the practical application of new inventions into marketable products or services

Who's Involved



Scientists

- Data Driven
- Precise language
- Reproducible results

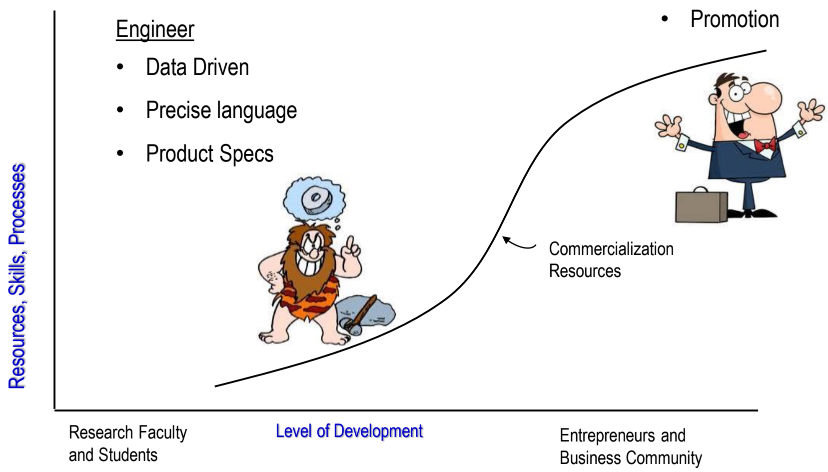
Who's Involved

MBA

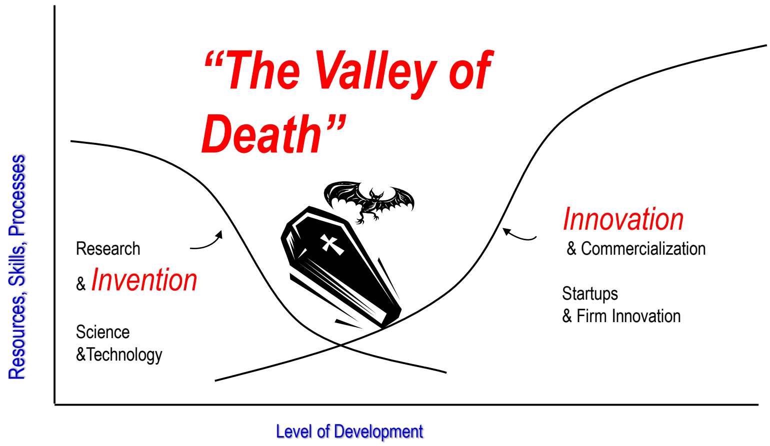
- Market share
- Profits
- Promotion

Engineer

- Data Driven
- Precise language
- Product Specs



The Problem:
The Gap between Research and Commercial Application



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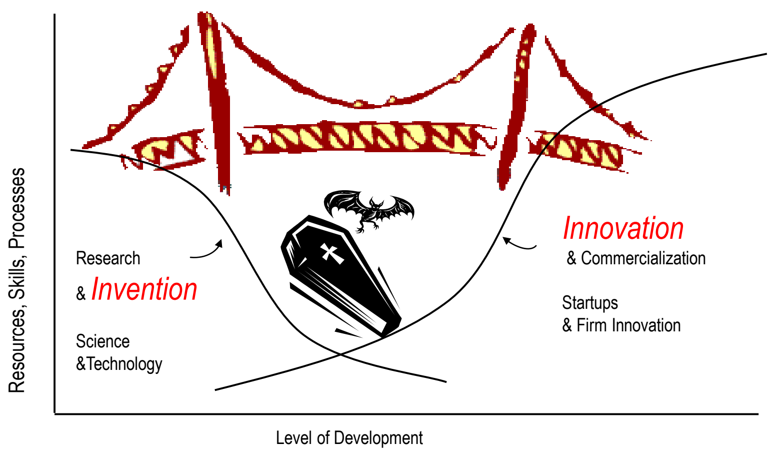


A process-based approach for capturing value from breakthrough innovation

An important *secret*

The "Entrepreneurship Process" NCSU teaches applies equally well to create and manage innovation

With a little help from our friends…

NSF

KENAN INSTITUTE
ENGINEERING, TECHNOLOGY & SCIENCE

$1,000,000

Local Impact

- Responsible for attracting $200+ Million of Venture Capital to Triangle companies
- Over 400 new jobs created
- 450+ graduates of the program
- Consulting and Training in Fortune 500 companies
- Adoption of the processes by large corporations

15+ Years of Experience and Results

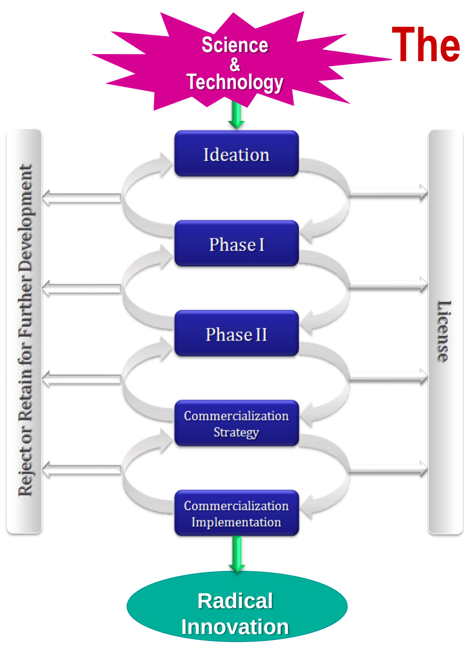
Start-ups and Licenses Created or Supported

HueMetrix, 3TEX, MYCOSOL, LIPS INC., Knowledge Sharing Systems, K, LipoMed, ArrayXpress, XANOFI, Atlantic Ozone Corporation, AAD Advanced Animal Diagnostics

Known Start-ups by TEC's Graduates

Protochips, Cronos, Nextreme Thermal Solutions, intervolve, RadarFind (Because Where Matters), Nitronex Corporation

The TEC Algorithm

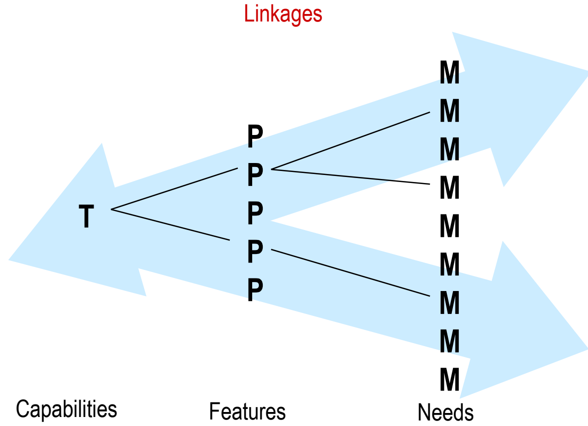


Transform Technology into Products/Services Concepts

Evaluate Opportunity

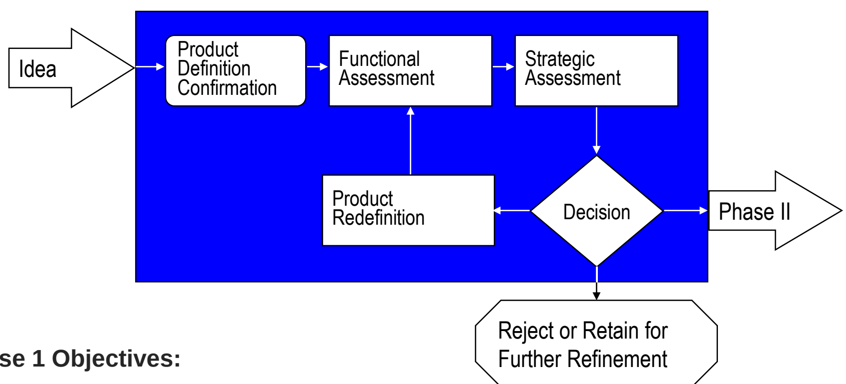
Strategy Development & Implementation

Technology ⟷ Product ⟷ Market



*** The foundation for business case development**

Phase 1 & 2 Assessments



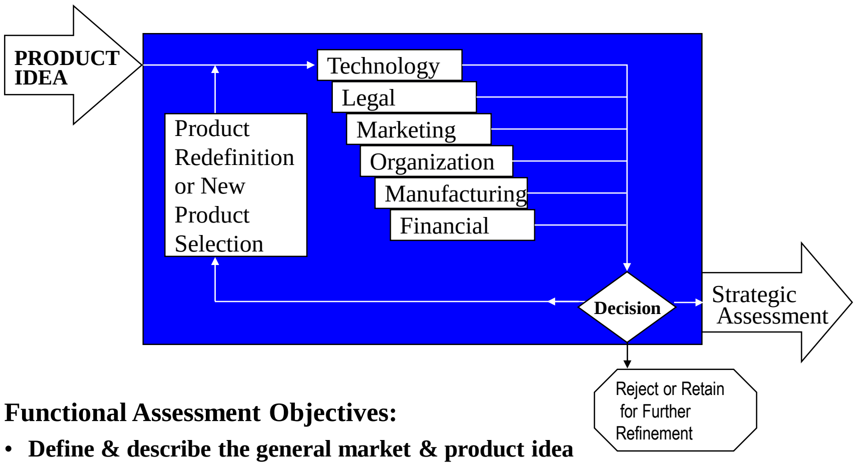
Phase 1 Objectives:

- To eliminate product ideas (not technologies) based on fatal flaws

Phase 2 Objectives:

- To build the business case

Functional Analysis



Functional Assessment Objectives:

- **Define & describe the general market & product idea**
- **Force an awareness check across functional areas**
- **Phase I - Search for fatal flaws, verify information and assumptions**

Information Gathering

a bottom-up approach

The Functional and Strategic Assessments provide guidance with regard to:

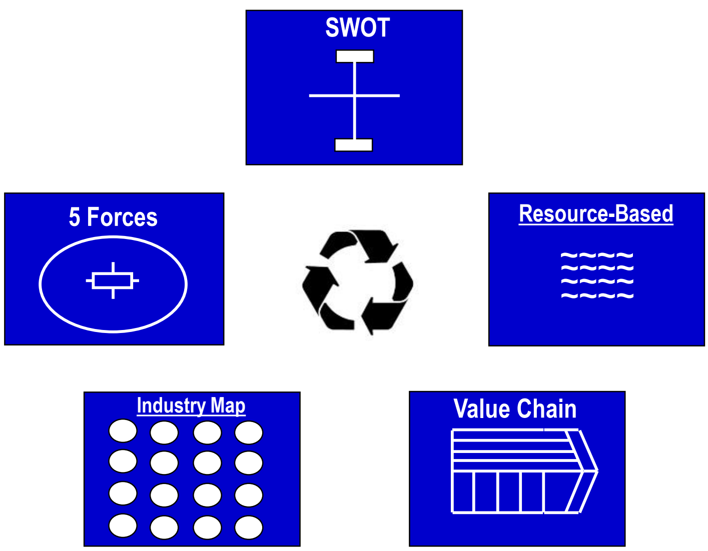
- The information that needs to be gathered
- Where to get the information (who to contact)

Near the end of Phase II a **"Voice of the Customer"** exercise is used to confirm need and product feature assumptions.

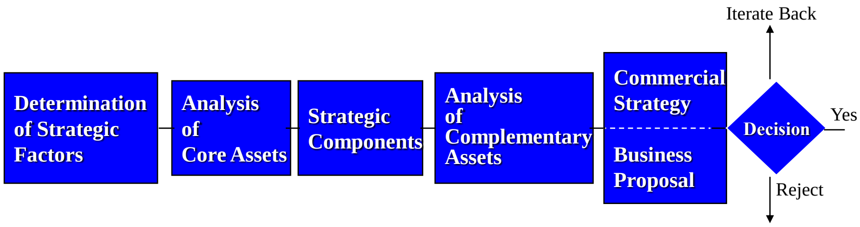
Voice of the Customer

- A complete set of customer wants and needs
- Expressed in the customer's own language
- Organized the way the customer thinks about, uses and interacts with the product or service
- Prioritized by the customers in terms of importance and performance, current satisfaction with existing alternatives

Strategic Assessment

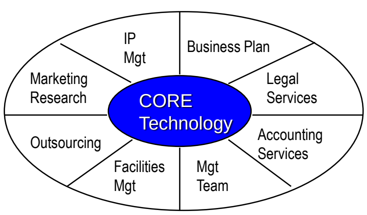


Commercialization Strategy Development



Provides a decision making process leading to the commercialization strategy and the business proposal.

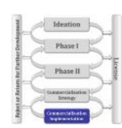
Creating a Viable Business Model



Building the Emerging Case

Putting the components together:

- ensure that the core technology is commercially viable
- identify required complementary resources
- make partnering, leveraging, and acquisition decisions regarding essential assets
- networking and placement of opportunity with partners & investors



Sarah Edge

CASL Market Analysis Project Lead
Accelerating Commercialization of Technologies

NCSU Poole College of Management MBA TEC Program Graduate

Email: sarah.edge@ashleighfisher.com
Phone: 425-749-1177

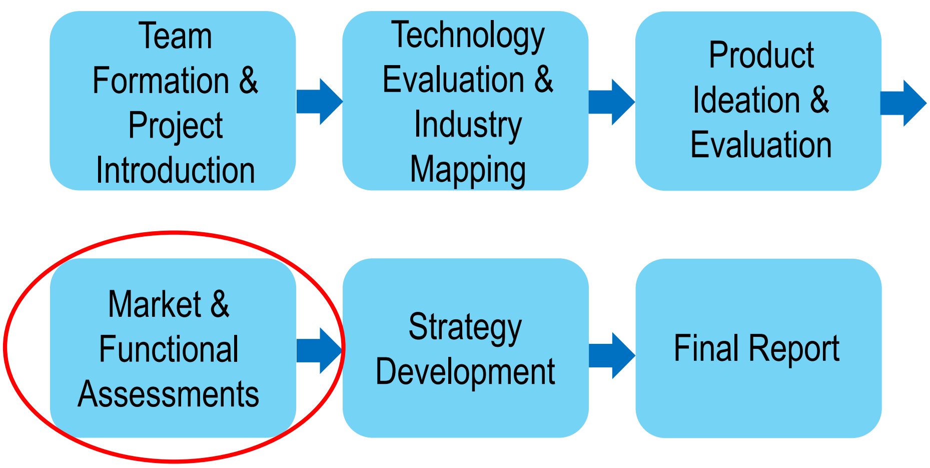
Agenda

- Market Analysis Goals
- Project Plan and Current Status
- Overview of Data Collection Process
- Raw Data Characteristics
- Next Steps

Market Analysis Goals

- Interview key stakeholders in commercial nuclear power space to determine potential industry value
- Using best available information, recommend potential business models for the post-CASL entity
  - Project goal is a business model for revenue-neutral organization at a minimum
  - Several options to be presented
- North Carolina State University Technology Entrepreneurship and Commercialization (TEC) is leading the effort

Project Plan



Voice of the Customer

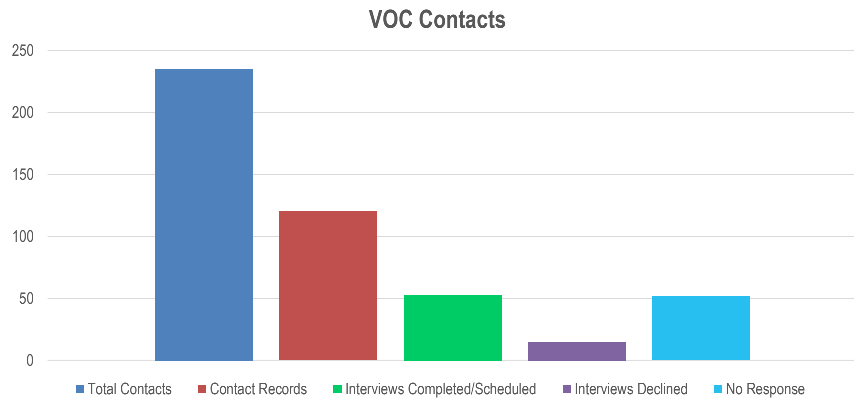
A process to capture data that encompasses:

- A complete set of customer wants and needs
- Expressed in the customer's own language
- Includes input from a broad spectrum of sources, including decision makers, potential competitors, end users, critics, etc
- One-on-one interviews when possible to promote open, anonymized discussion

Voice of the Customer Process

- Develop initial contact list, compile initial VOC questions, both general and specialized
- Assign contacts, initiate introductions, and conduct interviews
- Periodically regroup to discuss findings
- Update contact list and questions as needed
- Conduct follow up interviews as needed

Voice of Customer Statistics as of 11/2015

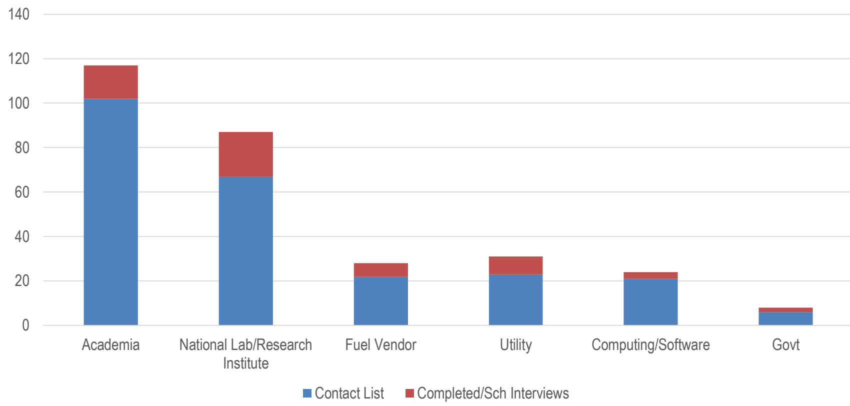


Voice of the Customer Statistics

Most interviews have been from categories:

- Academia
- Computing/Sim Software
- Fuel Vendor
- National Laboratory
- Research Institute
- Utility

Voice of Customer Categories



VOC Raw Data Characteristics

Caveat: too early to draw conclusions regarding recommendations or comprehensive insights

- Most data to date is from CASL members/partners
- Industry appears very slow to adopt new technologies
- Most commonly cited themes include VERA as a benchmarking tool, need for validation and licensing for safety applications

VOC Raw Data Characteristics

- VERA will require a significant support system post-CASL
  - Many believe it will require a number of years post-CASL to move beyond commercial early adopters and VERA.edu
  - Academics anxious to acquire VERA.edu
- Excitement regarding potential to allow for uprating and to take nuclear power generation to next level via fuel rod/reactor core design

Next Steps

- Continue VOC interviews, extending to more international and non-CASL members
  - Work closely with TDO to ensure consistency of messaging
  - Help is needed to facilitate and expedite data collection
  - Complete data collection, move toward strategy development, with draft report to TDO by end of January 2016

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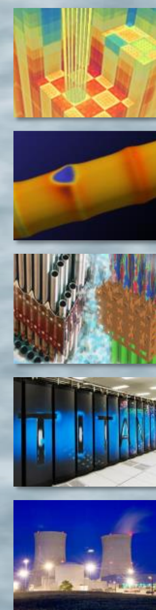
Questions?

CASL Science / Industry Council Meeting
November 4-5, 2015

Spotlight on Thermal Hydraulics Focus Area: CFD Progress & Path Forward



Emilio Baglietto
THM Focus Area Lead
Massachusetts Institute of Technology

Dave Pointer
THM Focus Area Deputy Lead
Oak Ridge National Laboratory

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U.S. DEPARTMENT OF ENERGY

Welcome Dave Pointer

THM Focus Area Deputy Lead

- Ph.D. Nuclear Engineering
The University of Tennessee
May 2001 Knoxville, TN
- M.S. Nuclear Engineering
The University of Tennessee
August 2000 Knoxville, TN
- B.S. Nuclear Engineering
The University of Tennessee
May 1997 Knoxville, TN

- Technical and Program Integrator, Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program
- Technical Lead, Nuclear Energy Advanced Modeling and Simulation (NEAMS) Reactor Product Line
- Lead, SHARP Nuclear Reactor Performance and Safety Simulation Suite Development Team

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INTRODUCTION

CFD Delivery
… a review

- **Three Steps aimed at "delivery"**

Code Evaluation: methods, performance, extendibility	**Phase-1 Development:** complete Hydra-TH 1 and 2P	**Phase-2 Delivery:** requirements vs. capabilities
Drekar Fuego … NPHASE TransAT STAR-CD STAR-CCM+	Hydra-TH Non-proprietary VERA component ▪ …full effort devel. ▪ …evaluate at the end of FY15 STAR-CCM+ ▪ Test bed for CLS ▪ … immediate availability	▪ **Commercial CFD** in support of addressing Challenge Problems. ▪ Ensure portability of closure models (platform independent) ▪ ***STAR-CCM+ base platform*** ▪ ***openFOAM prototyping*** ▪ ***NEPTUNE ; NEK5000 collaborations***

CASLTHM Delivered

- Excellent show of CASL capabilities at the NURETH-16 Conference (>10 papers)

Track 7: CASL—Thermal-Hydraulics Activities in the Consortium for Advanced Simulation of LWRS

Session Organizer: Elia Merzari (ANL)

7101 Mechanistic Modeling of Two-Phase Flow Around Spacer Grids with Mixing Vanes B. M. Waite, D. R. Shaver, M. Z. Podowski, (RPI)

7115 Interface Tracking Simulations of Bubbly Flows in the PWR Relevant Geometries Jun Fang (NCSU), Michel Rasquin (ANL), Igor A. Bolotnov (NCSU)

7129 Spectral Analysis of the Turbulent Energy Spectrum in Single and Two-Phase Bubbly Flows in Different Geometries Based on Direct Numerical Simulation Results C. S. Brown, I. A. Bolotnov (NCSU)

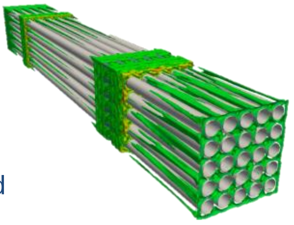
7143 Synthesis of CRUD and its Effects on Pool and Subcooled Flow Boiling Carolyn Coyle, Jacopo Buongiorno, Thomas McKrell, Robert Cohen (MIT)

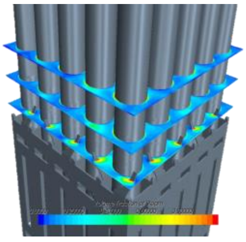
7154 CTF Validation Activities T. Blyth, C. Dances, M. Avramova (Penn State), R. Salko (ORNL)

Young Professional Award for Carolyn Coyle, with THM L2 work

Overview of Scope of Activities

- **Single Phase CFD:**
  - **GTRF:** Highly scalable and validated LES simulations
  - **CRUD/CILC:** Tight Coupling with MAMBA with Robust and improved Anisotropic RANS simulations
  - **Solutal/Thermal Driven Flows**: (P) Improved RANS/Hybrid methods for Buoyant Mixing
- **MultiPhase CFD:**
  - **DNB:** *Discovery* – next generation boiling closures and 1st principle based local DNB
  - **BWR Normal T-H Conditions:** (E) Robust predictions of local void fraction in fully resolved BWR assemblies



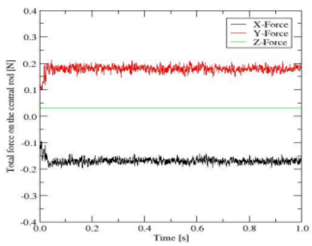


(P) = Planned
(E) = Expected, early stage

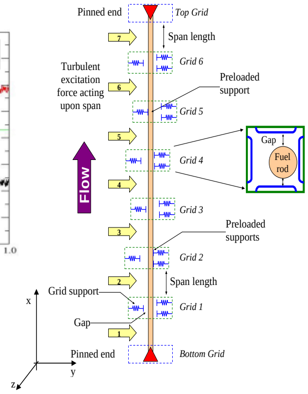
GRID TO ROD FRETTING [GTRF]

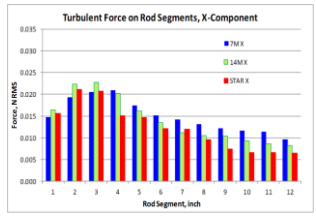
Highly scalable and validated LES simulations

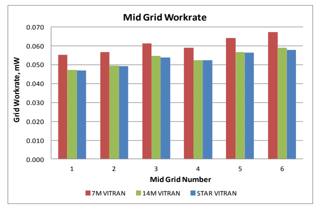
- Pressure Profiles and Rod Forces are extracted from LES for the 3x3 Rod Bundle
- The data are used as input to VITRAN to compute rod acceleration/displacement
- 7 to 14M meshes required for reasonable fidelity in design analysis ~ 8 – 24 hour calculations



Force time history data used for rod dynamic analysis, e.g., with VITRAN







2% difference between STAR-CCM+ and Hydra-TH wear work-rates

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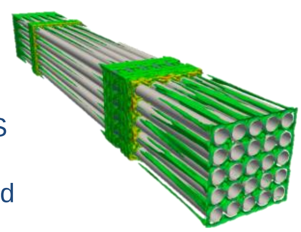

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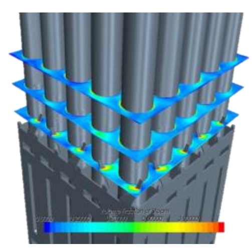


(P) = Planned
(E) = Expected, early stage

DNB demonstration approach

Model Development: minimal redundancy → accelerate deliv.

MIT: Mechanistic Microlayer representation

RPI: Continuous evaluation/improvement

NCSU: Data Driven

UMICH: CRUD/Boiling consistency and MAMBA/STAR assessement **[L2]**

Model Development Support: Focused experiments/DNS

NCSU: Pressure scaling/extrapolation, near wall behavior, turbulence mechanisms

ND: Swarm effects, near wall behavior

MIT: Flow boiling DNB microlayer measurements

TAMU: GEN-II boiling verification/extension. Turbulence/near wall measurements

Model Validation: requirements vs. capabilities

WH: Integral 5x5 measurements (DNB)

LANL: Broad validation database/support for 5x5 validations (DNB)

INL: GEN-II validation/pressure range extension

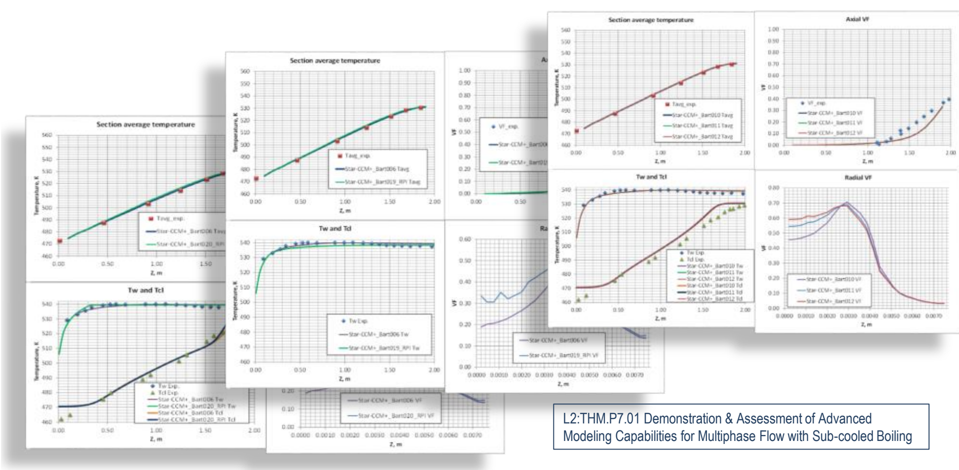
LANL-2: Collaboration with CEA for validation of fundamental capabilities

COLLABORATION: leverage external DNB databases for validation

Progress: mature baseline

- CASL Validation has Demonstrated Maturity of Closures
- Demonstrated Portability (STAR-CCM+, NPHASE)
- The DEBORA Test Case Results are shown below

MICHIGAN
V. Petrov, A. Manera



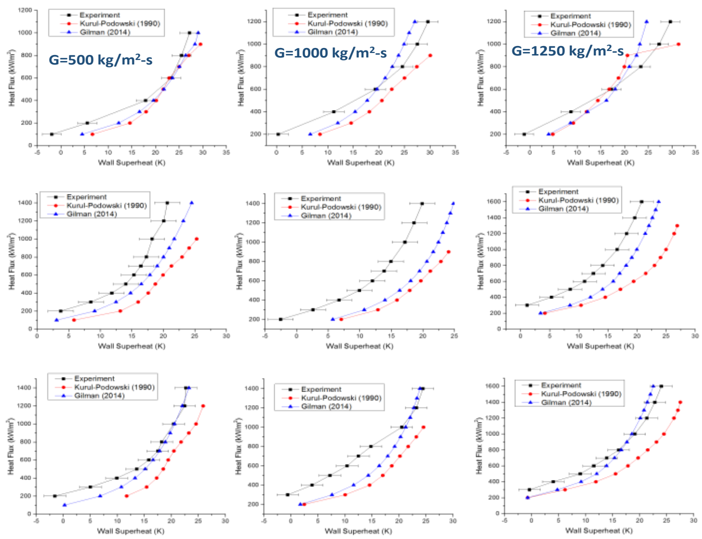
L2:THM.P7.01 Demonstration & Assessment of Advanced Modeling Capabilities for Multiphase Flow with Sub-cooled Boiling

Progress: Calibration-free Assessment
extensive microscale CASL database

1 bar 10°C subcooling

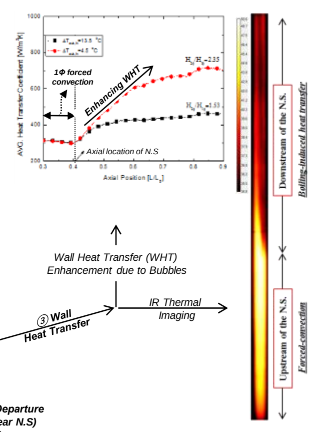
2 bar 10°C subcooling

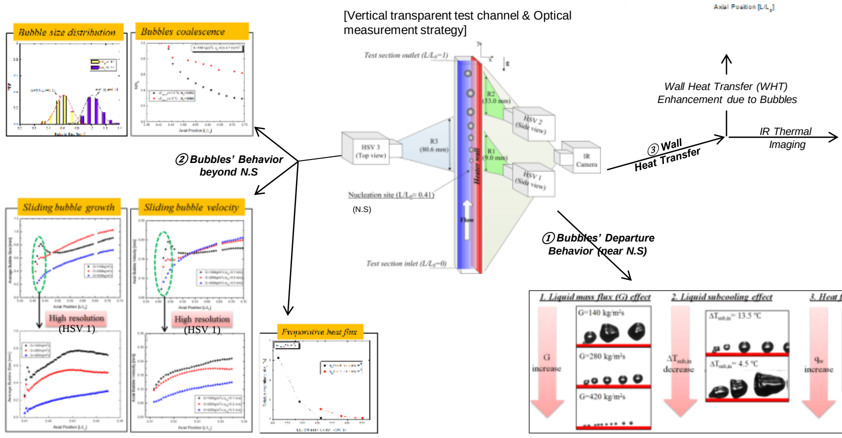
2 bar 15°C subcooling



Path Forward: Extending Validation
[INL JunSoo Yoo]

***TAMU Subcooled Flow Boiling Experiments with Refrigerant** (multi-scale, multi-physics, high-reliability)*

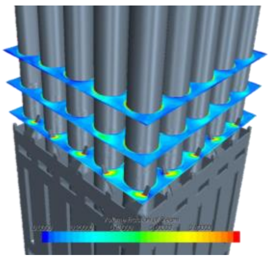




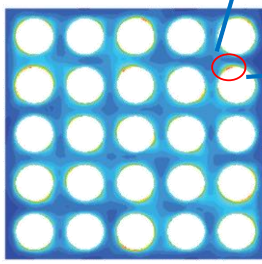
Departure from Nucleate Boiling in CFD

Why M-CFD for DNB Predictions

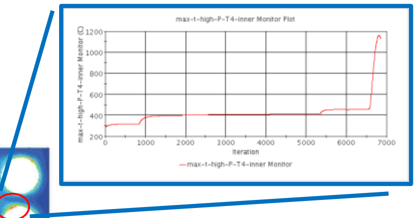
- Leverage accurate 3D predictions of CFD to improve prediction of DNB.



void fraction



DNB



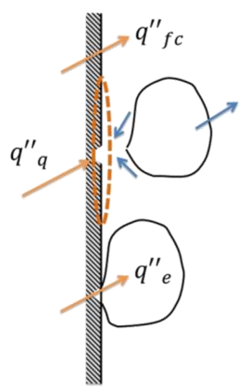
- Even existing DNB macroscopic methods + CFD should provide improved accuracy

Zeses Karoutas “Use of CFD to Predict Critical Heat Flux in Rod Bundles” – NURETH16

The simple way: Macrolayer Models in CFD

- Heat transfer regime transition enforced when DNB criterion is reached.
- $q_{wall} = f_\alpha \left(q_{fc} + q_{ev} + q_q\right) + (1 - f_\alpha)q\_v$

- Current criterion ***“a la Weisman & Pei”***
  $\boldsymbol{\alpha_{crit} = 82\%}$
- f_α is a blending function
  - $f_\alpha = 1$ for pre-DNB nucleate boiling regime
  - $f_\alpha = 0$ for post-DNB inverted film boiling regime



Nucleate Boiling partitioning model

From Gilman Ph.D. Thesis (2013)

Macrolayer Models in CFD: a recent view

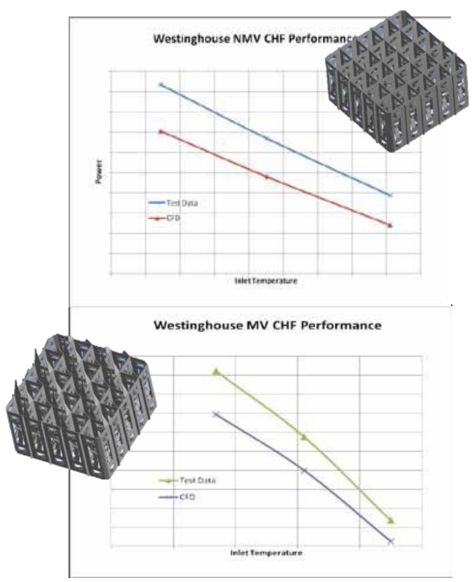
NURETH-16 Panel Session

- Stephane Mimouni *(EdF)*, "Computational Multi-Fluid Dynamics Predictions of DNB"
- Zeses Karoutas *(WEC)*, "Use of CFD to Predict Critical Heat Flux in Rod Bundles"
- Simon Lo *(CD-Adapco)*, "Bubble Dynamics in DNB"
- Nam T. Dinh *(NCSU)*, "Predictability of Boiling Heat Transfer and Burnout at High Heat Fluxes"
- Hyungdae Kim, *(KHU),* "High-Resolution Study of Nucleate Boiling and DNB using Integrated Visible and Infrared Imaging"

Macrolayer Models in CFD: experience-1

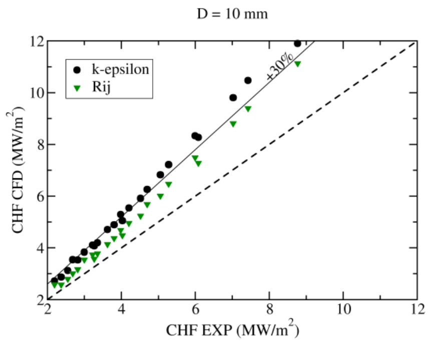
Zeses Karoutas (WEC):

- CFD predictions for CHF were made for 3 non-mixing vane cases and 3 mixing vane cases for a constant pressure &flow
- CFD comparisons compared to CHF data versus inlet temp.
- DNB predictions show very similar trends "out of the box"
- My comment: "WH recognizes both potential and limitations of the method (.. maturity)



Macrolayer Models in CFD: experience-2

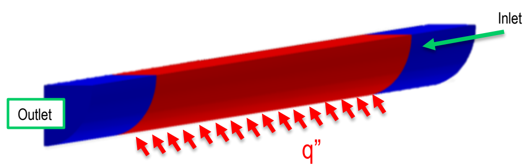
- Other authors make more daring claims <10% error in specific conditions.
- No real “best practice” for physics model selection.
  - Interfacial forces (drag, lift, turb. dispersion, virtual mass, wall lubrication…)
  - Boiling model (“RPI” wall partitioning model)
  - DNB criterion (where is α_{crit} measured? 82% = optimal value?)

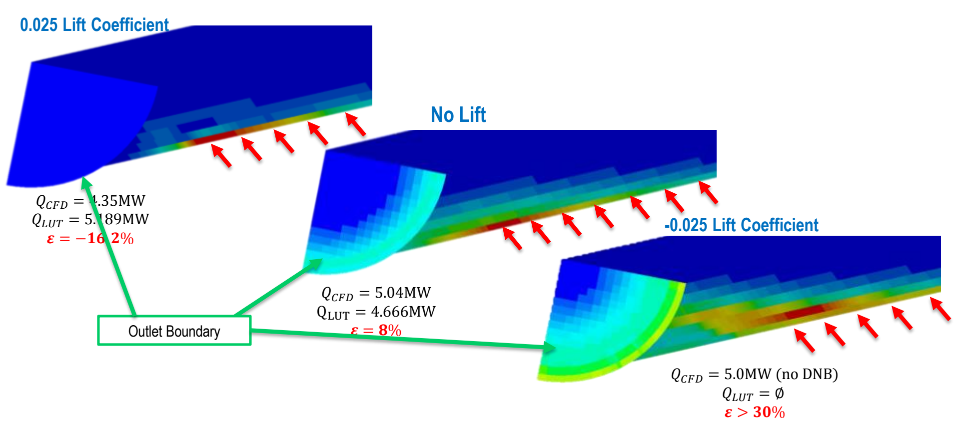


1. **S Mimouni**, C Baudry, M Guingo, J Lavieville,N Merignoux, and N Mechitoua. **Computational multi-fluid dynamics predictions of critical heat flux in boiling flow.** In *CFD4NRS-5*, September 2014.

A simple example: sensitivity to lift coefficient

- Single tube (8mm)
- Pressure: 100 bar
- Inlet quality: -0.24
- Inlet mass flux: 3000 $\frac{\text{kg}}{\text{m}^2\text{s}}$
- Constant heat flux
- Reference CHF: Groeneveld 2006
- Constant lift





A new “microlayer”DNB mechanism

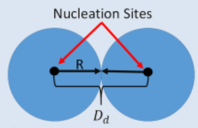
- Bubbles merge on heater surface prior to departure
  - Indicates size of dry surface patches

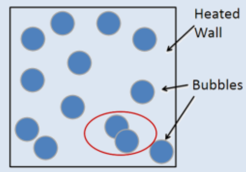
Fraction of nucleation sites ACTIVE at a point in time

$$N_b'' = f t_g N''$$

$$P = 1 - e^{-N_b'' \pi D_d^2}$$

complete spatial randomness methods (CSR)

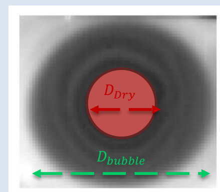




- Track the wet and dry surface in a “cell”
  - This allows splitting the heat transfer into 2 components where

$$q"_{tot} = A_{dry}\, q"_{vapor\_film} + (1 - A_{dry}) q"_{Nucleate}$$

.. as the heat flux increases, heat removed by the wetted area can’t keep up, leading to larger coalescence between bubbles, and further decreases in wetted area, resulting in surface dryout.



H. Kim, J. Buongiorno, “Detection of Liquid-Vapor-Solid Triple Contact Line in Two-Phase Heat Transfer Phenomena Using High-Speed Infra-Red Thermometry”, *Int. J. Multiphase Flow*, 37, 166-172, 2011

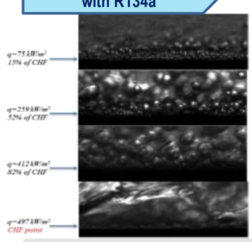
Path Forward: Extend DNB validation

LANL Seung Jun Kim

Seung Jun Kim, et. Al. An experimental study on sub-cooled flow boiling CHF of R134a at low pressure condition with atmospheric pressure (AP) plasma assisted surface modification, International Journal of heat and mass transfer, 81(2015) 362-372

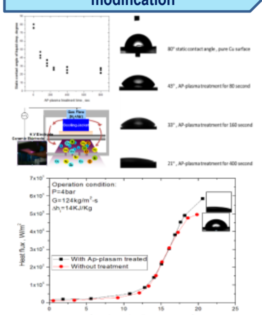
1. New role of LANL to support DNB Validation
   - Driven by Seung Jun Kim – leverage both experimental and CFD experience
   - Leverages LANL extensive experience (D.V. Rao, Director for Civilian Nuclear Program)
   - Boiling Model validation (Gen. I and II) using Starccm+ on the LANL cluster
     - 5x5 fuel bundle geometry DNB test and comparison with WEC DNB data
2. Flow boiling CHF enhancement test with modified surface and prediction model development
   - Hydrophilic surface fabricated by Atmospheric Plasma
   - Mechanical bubble force balance based CHF model

Flow boiling CHF test with R134a

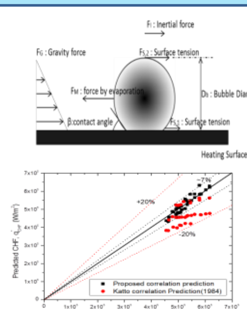


Flow boiling CHF test
- Flow rate effect
- Pressure effect
- Subcooling effect
- Flow visualization using HSC
- Surface effect

CHF enhancement with surface modification



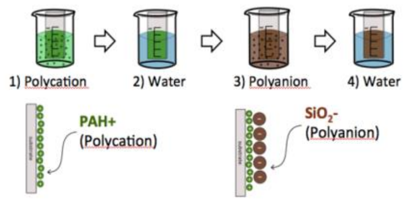
Development of CHF model based on Mechanical bubble force balance



L2:THM.P11.02

Experimental Determination of the Effects of (Synthetic) CRUD on Subcooled Boiling

• Carolyn Coyle, Jacopo Buongiorno*, Thomas McKrell - MIT

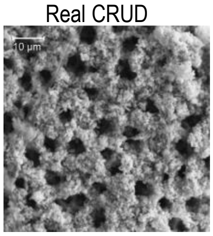


Layer-by-Layer Deposition of 100 nm SiO2 particles

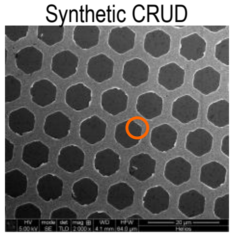
Table III. Synthetic CRUD test matrix.

Properties	Synthetic CRUD
Thickness	5, 10, 15 μm
Chimney Diameter	5, 10 μm
Chimney Pitch	10, 25, 100 μm
Subcooling	0, 5°C
Mass Flux	150, 250, 500, 750, 1000, 1250 kg/m^{2}s

Real CRUD



Synthetic CRUD



- Tests were conducted in a flow boiling loop.
- The composition of the synthetic CRUD varied to determine thickness and chimney pitch and diameter effect on boiling

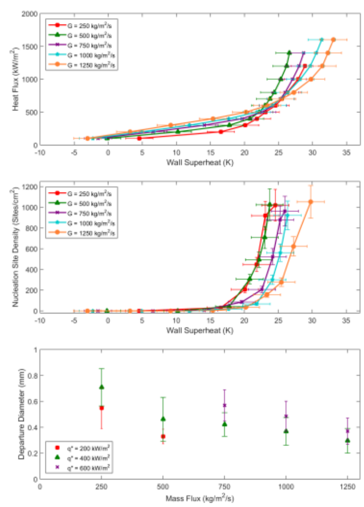
(thin) CRUD Effects on Boiling → DNB

- Large database of separate effects, thickness, chimneys, etc..
- First conclusions consistent with GEN-II boiling "*pre*"-dictions

Parameter	Case	Thickness	Diameter	Pitch
Effect of LbL	0	Bare	No chimneys	No chimneys
	2	2 μm	10 μm	25 μm
Effect of Chimneys	1	2 μm	No chimneys	No chimneys
	2	2 μm	10 μm	25 μm
Effect of Thickness	2	2 μm	10 μm	25 μm
	3	4 μm	10 μm	25 μm
Effect of Pitch	2	2 μm	10 μm	25 μm
	4	2 μm	10 μm	45 μm
Effect of Diameter	2	2 μm	10 μm	25 μm
	5	2 μm	12.7 μm	27.5 μm

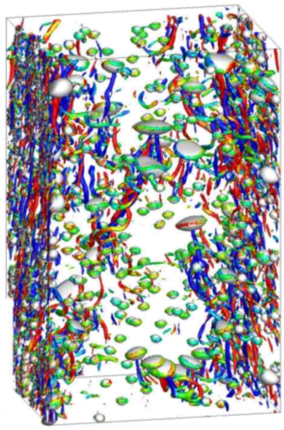
- Next step (DNB) driven by the modeling framework (e.g. evaluate dry surface area)

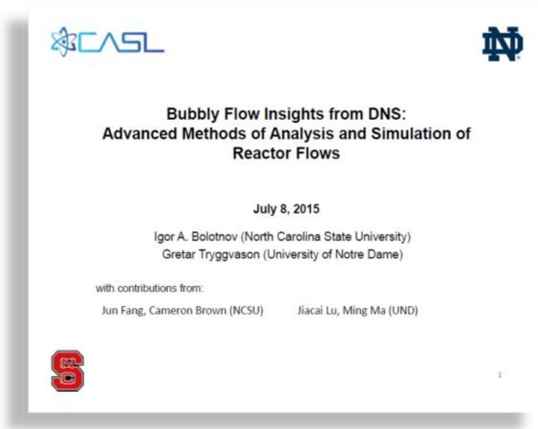
FY16: Experimental Study of Subcooled Flow Boiling Heat Transfer up to the DNB Limit



The role of ITM / DNS

- CASL SUCCESS: Effective use of Multiphase DNS to support closure model development.
- THM feature presentation highlights exceptional contribution of CASL Team Members



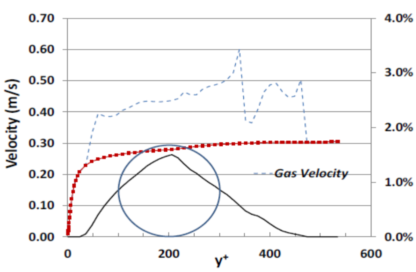


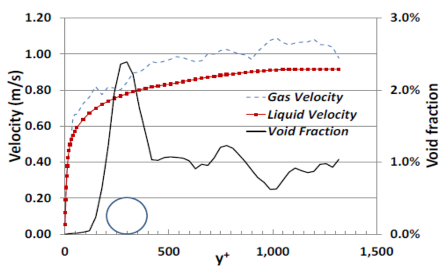
Flexibility of DNS for model scaling

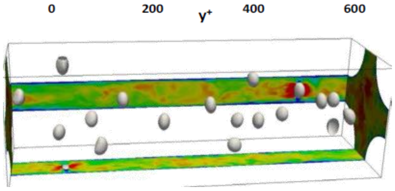
Igor Bolotnov NCSU

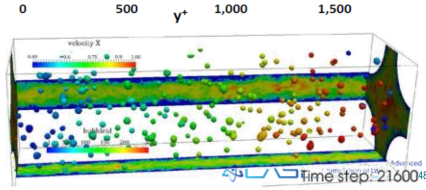
- Currently supporting hydrodynamic scaling to reactor pressure conditions
- Further extending to high void fraction conditions (see next slides)

Case	RE01	RE02	PWR operating conditions
Liquid/Gas Viscosities (Pa·s)	8.585x10^{-5}; 1.965x10^{-5}		
Liquid/Gas Densities (kg/m³)	712.22; 46.17		
Mean velocity (m/s)	0.27	0.75	4.62
Reynolds number (Re_b)	29,079	80,774	452,500









BWR capabilities approach

Model Development: 2 stage development: baseline vs CASL.

MIT/ANL: Collaboration with NEAMS to assemble reference closure

RPI: Separate model develoment/validation

WH: Support model assessment

Model Development Support: Focused experiments/DNS

NCSU/ND: Churn flow regime data/analysis

ND: Swarm effects, near wall behavior

COLLAB: HZDR Topflow data subset + KTH (ongoing)

Model Validation: requirements vs. capabilities

BFBT: Full bundle tests detailed VF measurements

HZDR: TOPFLOW complete database (potentially MT loop)

FRIGG test loop: closure development

RISO Lab: closure development

COLLABORATION: need to leverage external collaborations

Replicating the PWR approach: step 1 re-evaluation

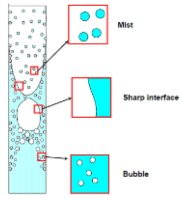
- Selected reference BWR Closures, and established collaborations
- Implemented reference test case
- Charging ahead with assessment of closures
- *SCOPE: understand what we don't know, evaluate portability*

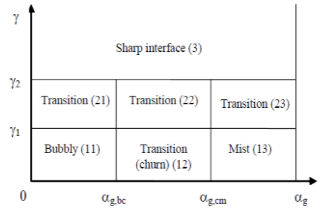
	Simplified	**HZDR**	**ANL EBF**
Interaction Length Scale	Constant = 1mm	Correlation (Yoneda + exponential + const)	Kurul&Podowski
Interaction Area Density	Symmetric	Spherical	Spherical
Lift	Constant = - 0.025	Tomiyama	Ohnuki&Akimoto
Drag	Tomiyama + Volume Fraction Exponent	Ishii-Zuber + Simonnet	Schiller&Naumann + correlation
Turbulent dispersion	Favre Averaged Drag Turbulent Pr = 1.0	Favre Averaged Drag Turbulent Pr = 0.9	Lopez de Bertodano (PhD, 1992)
Virtual Mass	Auton (spherical particle)	Auton (spherical particle)	Auton (spherical particle)
Wall lubrication	Antal	Hosokawa	Antal + topology map

Condensation - Fluid	Chen-Mayinger	Chen-Mayinger	Chen-Mayinger
Condensation - Vapor	Nu = 2.0	Nu = 2.0	Nu = 2.0

ANL EBF closure (Tentner et al.)

Collaboration with NEAMS





Bubble diameter → Kurul & Podowski

$$d = \begin{cases} \dfrac{d_1(\Delta T_{sub} - \Delta T_0) + d_0(\Delta T_1 - \Delta T_{sub})}{\Delta T_1 - \Delta T_0}, & \Delta T_1 \leq \Delta T_{sub} \leq \Delta T_0 \\ d_0, & \Delta T_{sub} \geq \Delta T_0 \\ d_1, & \Delta T_{sub} \leq \Delta T_1 \end{cases}$$

$$d_0 = 1.5x10^{-4} \quad d_1 = 2x10^{-3} \quad \Delta T_0 = 13.5 \quad \Delta T_1 = -5$$

Interaction Area Density → spherical

$$a = \frac{6\alpha_g}{d}$$

Turbulent Dispersion force → Lopez de Bertodano (field function)

$$F_{TD} = C_{\mathrm{TD}} \rho_c k_c \nabla \alpha_c$$

$$C_{\mathrm{TD}} = 0.1$$

$$F_{TD} = \left(\frac{1}{8} C_D a\, \rho_c u_r\right) \frac{\nu_c^t}{\sigma_\alpha} \left(\frac{\nabla \alpha_d}{\alpha_d} - \frac{\nabla \alpha_c}{\alpha_c}\right)$$

$$\sigma_\alpha = \frac{C_D u_r\, a\, \nu_c^t}{8 C_{\mathrm{TD}} k_c} \left(\frac{\alpha_c \nabla \alpha_d - \alpha_d \nabla \alpha_c}{\alpha_d \alpha_c \nabla \alpha_c}\right)$$

Lift force → Ohnuki & Akimoto (field function)

$$F_{Ld} = C_L \alpha_d \rho_c \boldsymbol{u_r} \times (\boldsymbol{\nabla} \times \boldsymbol{u_c}) \qquad u_r = |u_g - u_l|$$

$$C_L = C_{LF} + C_{WK} \qquad C_{LF} = 0.288 \tanh(0.121 Re_d) \qquad Re = \frac{\rho_l |u_r| d}{\mu_l}$$

$$C_{WK} = \begin{cases} 0, & Eo < 4 \\ -0.096 Eo + 0.384, & 4 < Eo < 10 \\ -0.576, & Eo > 10 \end{cases} \qquad Eo = \frac{g(\rho_l - \rho_g) d^2}{\sigma}$$

(only in bubbly topology)

Drag force →

$$F_D = \frac{1}{8} C_D \rho_c u_r^2 A_i$$

- bubbly flow (Schiller & Naumann) $C_D = \begin{cases} \dfrac{24}{Re}(1 + 0.15 Re^{0.687}) & 0 < Re \leq 1000 \\ 0.44 & Re > 1000 \end{cases}$

- mist flow $C_D = \dfrac{24}{Re} + \dfrac{5.48}{Re^{0.573}} + 0.36$ (only in bubbly and mist topology)

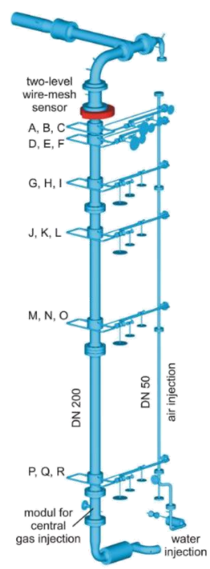
Collaboration with HZDR, Germany

- Leverage the TOPFLOW L12 experiments (dedicated to CFD validation)
  - *Diameter: 48.3 mm and 195.3 mm*
  - *Length: 8000 mm*
  - *Injection of gas via wall orifices with diameters of 1 and 4 mm*

- **Superficial Gas Velocity: 0.0025 to 18.97 m/s**
- **Superficial Liquid Velocity: 0.0405 to 4.047 m/s**

Superficial gas velocity J_G [m/s]

Superficial water velocity J_L [m/s]	0.0025	0.004	0.0062	0.0096	0.0151	0.0235	0.0368	0.0574	0.0898	0.14	0.219	0.342	0.534	0.835	1.305	2.038	3.185	4.975	7.772	12.14	18.97
4.047	011	022	033	044	055	066	077	088	099	110	121	132	143	154	165	176	187	198	209	220	231
2.554	010	021	032	043	054	065	076	087	098	109	120	131	142	153	164	175	186	197	208	219	230
1.611	009	020	031	042	053	064	075	086	097	108	119	130	141	152	163	174	185	196	207	218	229
1.017	008	019	030	041	052	063	074	085	096	107	118	129	140	151	162	173	184	195	206	217	228
0.641	007	018	029	040	051	062	073	084	095	106	117	128	139	150	161	172	183	194	205	216	227
0.405	006	017	028	039	050	061	072	083	094	105	116	127	138	149	160	171	182	193	204	215	226
0.255	005	016	027	038	049	060	071	082	093	104	115	126	137	148	159	170	181	192	203	214	225
0.161	004	015	026	037	048	059	070	081	092	103	114	125	136	147	158	169	180	191	202	213	224
0.102	003	014	025	036	047	058	069	080	091	102	113	124	135	146	157	168	179	190	201	212	223
0.0641	002	013	024	035	046	057	068	079	090	101	112	123	134	145	156	167	178	189	200	211	222
0.0405	001	012	023	034	045	056	067	078	089	100	111	122	133	144	155	166	177	188	199	210	221



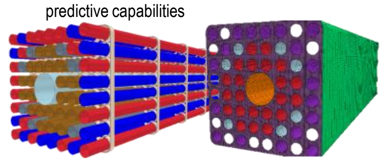
Gustavo Montoya, PhD

OECD/NEA BFBT Benchmark
Experiment 4101-61

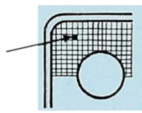
- High quality void fraction data in BWR bundle

X ray Scanner data:
- pixel-void fraction (%)
- sub-channel averaged void fraction (%)
- cross-sectional averaged void fraction (%)

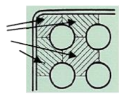
NUPEC BWR Full-size Bundle Test (BFBT)
- Provides robust validation of closures predictive capabilities

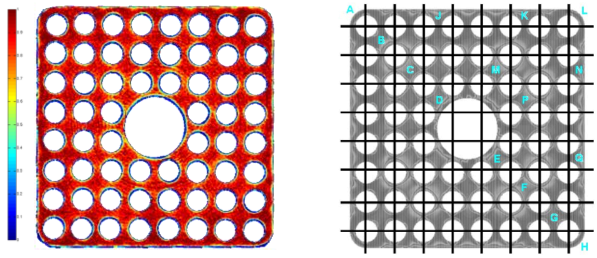


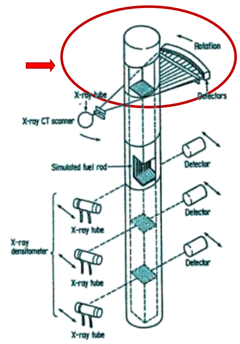
Pixel void fraction



Sub-channel void fraction

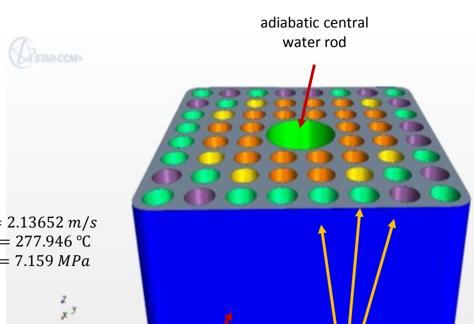






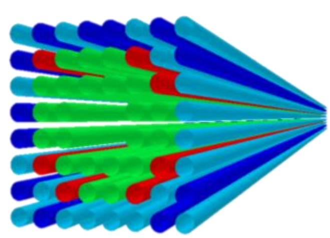
OECD/NEA BFBT Benchmark (2)
Experiment 4101-61

$Tsat = 287.388℃$



- Uniform axial power profile
- Design simulated radial power profile (4 coefficients multiplied by 751497 W/m2)

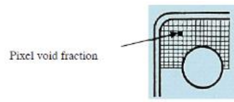
1.15	1.30	1.15	1.30	1.30	1.15	1.30	1.15
1.30	0.45	0.89	0.89	0.89	0.45	1.15	1.30
1.15	0.89	0.89	0.89	0.89	0.89	0.45	1.15
1.30	0.89	0.89			0.89	0.89	1.15
1.30	0.89	0.89			0.89	0.89	1.15
1.15	0.45	0.89	0.89	0.89	0.89	0.45	1.15
1.30	1.15	0.45	0.89	0.89	0.45	1.15	1.30
1.15	1.30	1.15	1.15	1.15	1.15	1.30	1.15



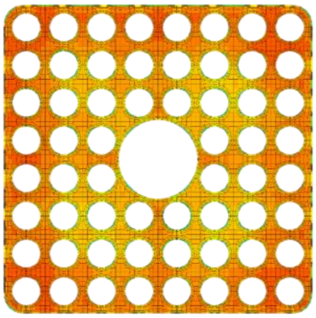
Simplified Boiling Model Results

Runtime on Workstation
10cores / ~40hours
*discussed challenge of source terms requires high under-relaxation

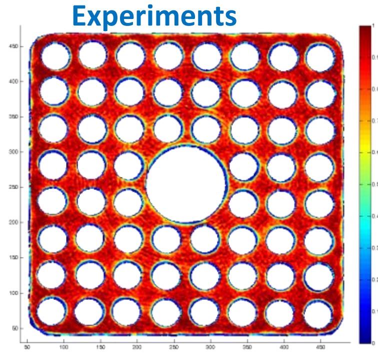
Pixel Void Fraction X-ray scanner plane



CFD

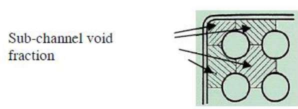


Experiments

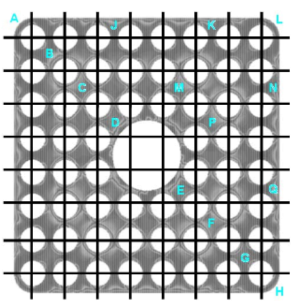


Simplified Boiling Model Results

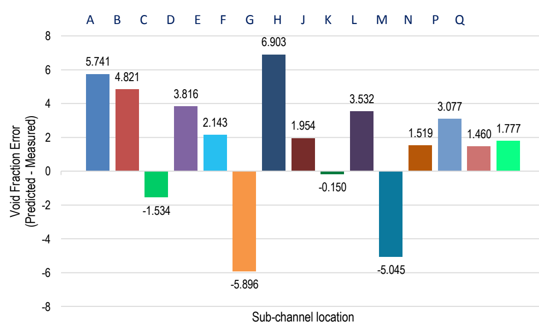
Sub-channel averaged Void Fraction (%)
X-ray scanner plane



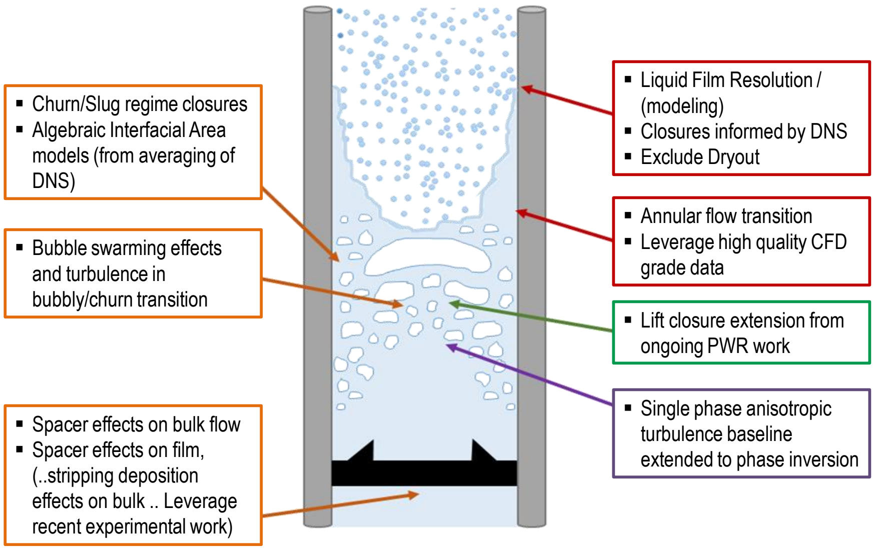
15 different sub-channel locations



$$\mathrm{E}[\%] = \alpha_{predicted} - \alpha_{measured}$$



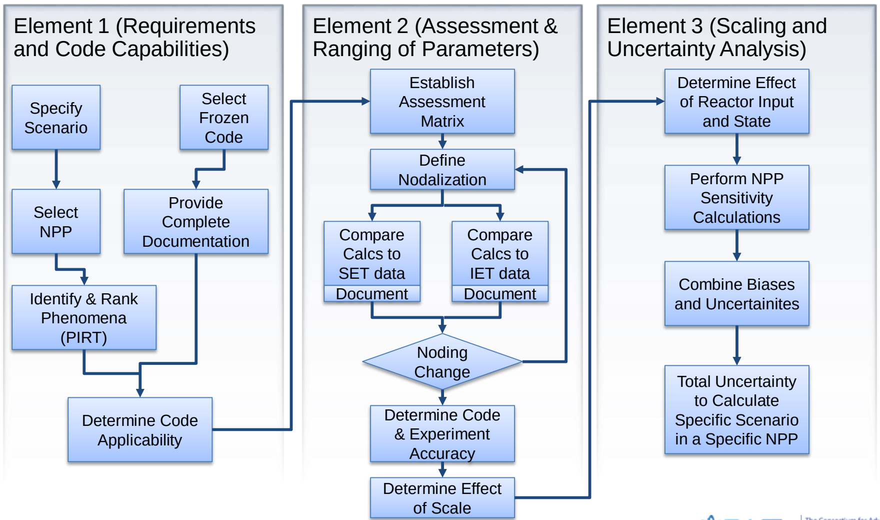
BWR Path Forward: separate effects



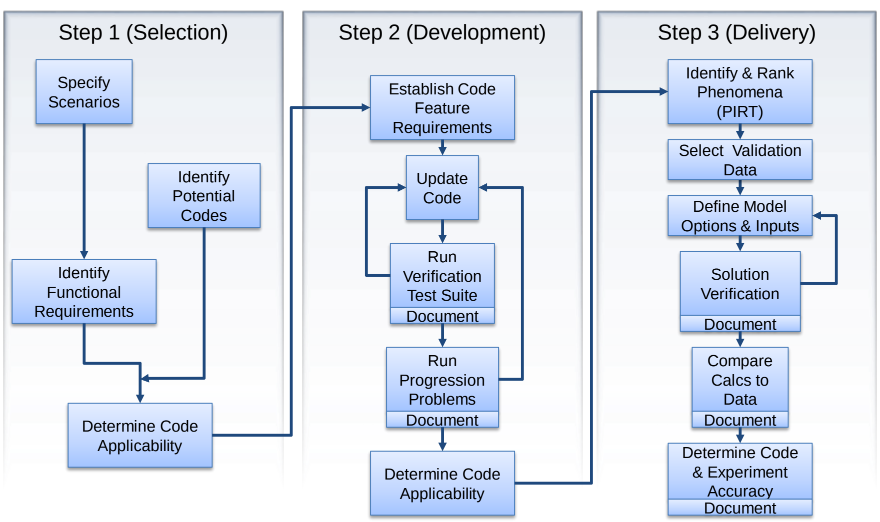
CASL THM V&V PLAN

NRC PATHWAY FOR CODE VVUQ

CODE SCALING, APPLICABILITY, AND UNCERTAINTY EVALUATION METHODOLOGY (CSAU)



THM SOFTWARE ASSESSMENT (VVUQ)



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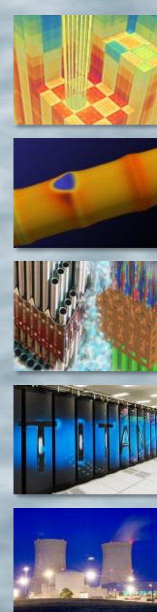
Status of Challenge Problems Progress Made: Overview

Science Council / Industry Council
November 4, 2015
Zeses Karoutas
Overall Challenge Problem Integrator
Westinghouse Electric Co.



The Consortium for Advanced Simulation of LWRs
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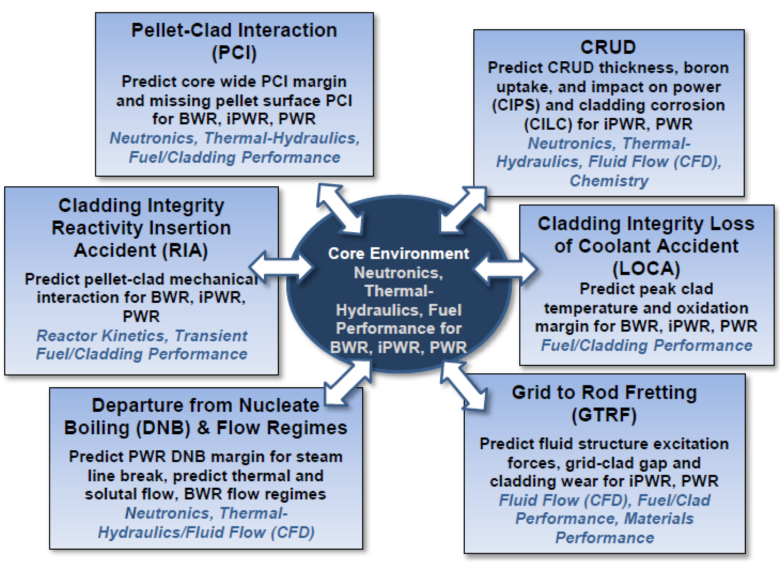
U.S. DEPARTMENT OF ENERGY

Outline

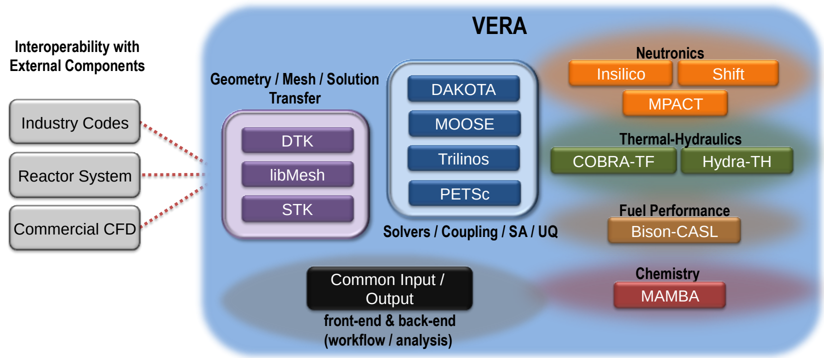
- Review of Challenge Problems
- Challenge Problem Integrators*
  - **CRUD** **Jeff Secker**
  - **PCI** **Joe Rashid**
  - **DNB** **Yixing Sung**
  - **RIA & LOCA** **Gregg Swindlehurst**
  - **GTRF** **Brian Wirth**
  - VALIDATION Nam Dinh
- Summary

* Presentations in bold

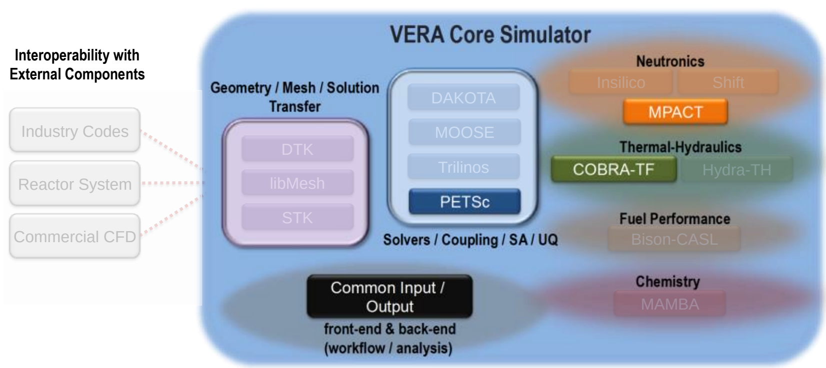
Challenge Problem Scope – Phase 2



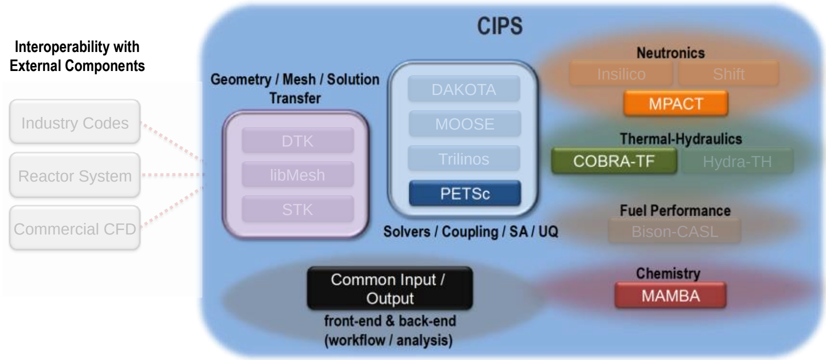
Virtual Environment for Reactor Applications (VERA) – Challenge Problems



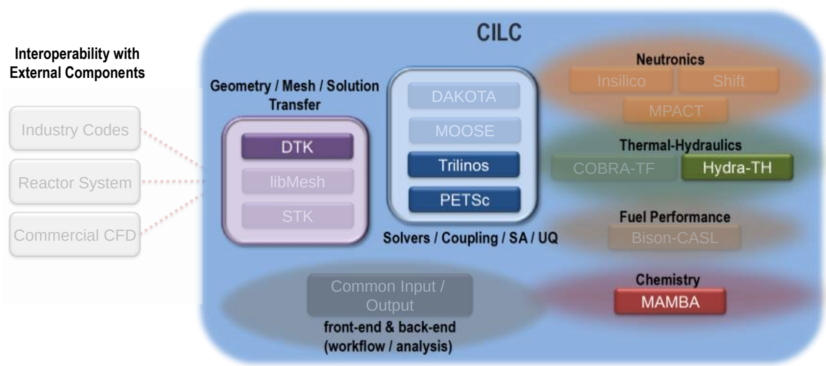
VERA Core Simulator Couples Components for Simulating Steady State Operation



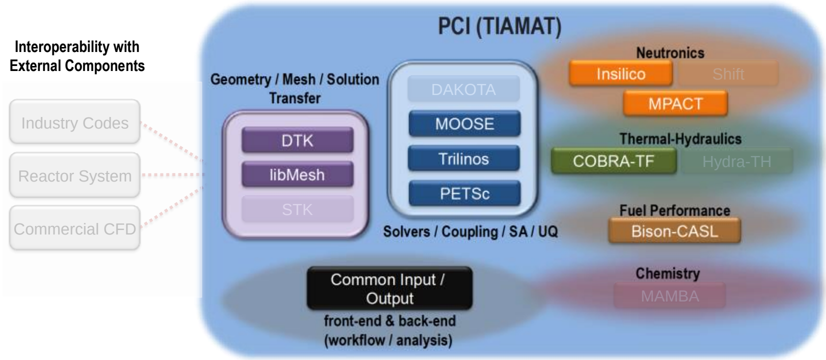
VERA for CRUD Induced Power Shift Component Coupling



VERA for CRUD Induced Localized Corrosion – Component Coupling



VERA for Pellet Clad Interaction Component Coupling



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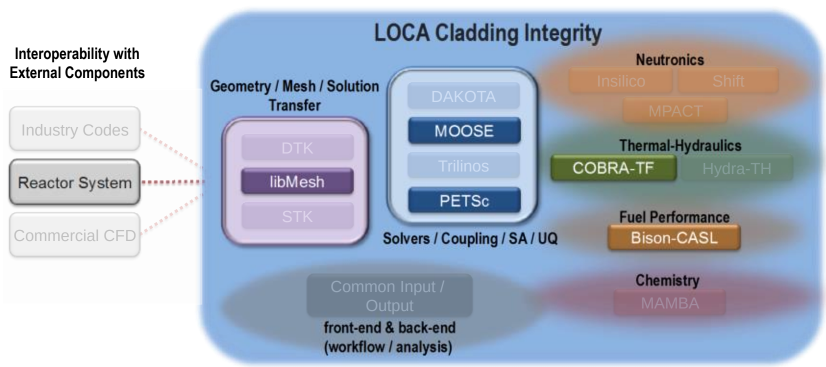
VERA for LOCA Cladding Integrity Component Coupling



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Summary - Overall Challenge Problem Progress Phase 2

	Development	Innovation	Validation
Operational			
CRUD-induced power shift (CIPS) – PWR/iPWR	Significant Progress	Significant Progress	Good Progress
CRUD-induced localized corrosion (CILC) – PWR/iPWR	Significant Progress	Significant Progress	Good Progress
Grid-to-rod fretting failure (GTRF) – PWR/iPWR	Significant Progress	Significant Progress	Good Progress
Pellet-clad interaction (PCI) – PWR/iPWR	Significant Progress	Significant Progress	Good Progress
Pellet-clad interaction (PCI) - BWR	Significant Progress	Significant Progress	Planning & Scoping
Safety			
Departure from nucleate boiling (DNB) – PWR/iPWR	Significant Progress	Significant Progress	Good Progress
Cladding integrity during (LOCA) – PWR/iPWR	Good Progress	Planning & Scoping	Not Started
Cladding integrity during (RIA) – PWR/iPWR	Good Progress	Planning & Scoping	Not Started
Predict Thermal & Solutal Flows – iPWR/BWR	Planning & Scoping	Not Started	Not Started
Cladding integrity during (LOCA) – BWR	Planning & Scoping	Not Started	Not Started
Cladding integrity during (RIA) – BWR	Planning & Scoping	Not Started	Not Started

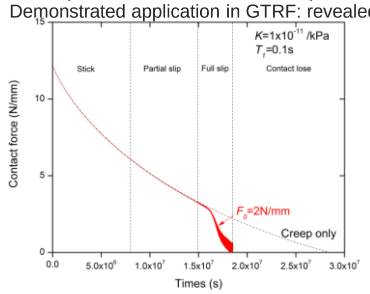
Significant Progress | Planning & Scoping

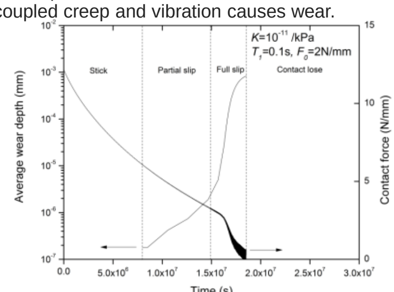
Good Progress | Not Started

GTRF CP: Fretting mechanics: evaluating relaxation of contact stress between clad & grid

Accomplishments

- Developed an effective and efficient pseudo-cycle technique
- Demonstrated application in GTRF: revealed how coupled creep and vibration causes wear.





Wear evolves through 3 stages during operation

- Stick: no relative sliding and no wear
- Partial slip: wear at the edge of the contact area
- Full slip: significant wear

Dominant stress-relaxation mechanism changes during operation

- In stick and partial slip stage: creep dominates
- In full-slip stage: creep and wear are both important

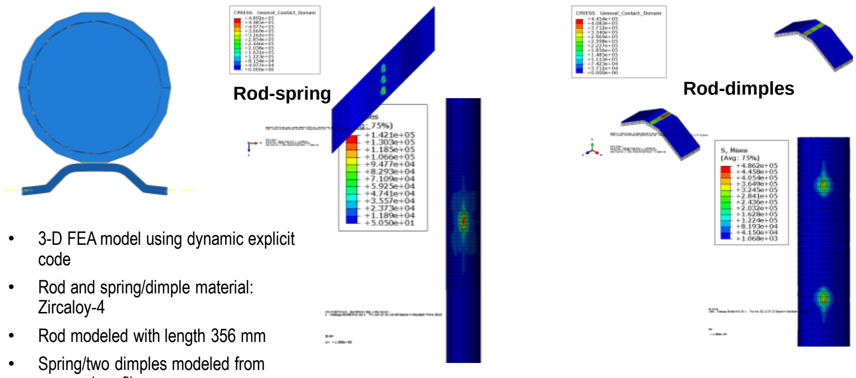
Simulation approach

Wear	pseudo-cycle technique	Creep
• Turbulence-induced vibration as applied force • Archard's law for wear • Wear simulation: fictitious eigenstrain algorithm [1]		• Gauge pressure on the cladding surface • High temperature of cladding : 600K • Creep simulation: Mechanism-based framework [2]

[1]Z. Hu , W. Lu , M. D. Thouless, and J. R. Barber, "Simulation of wear evolution using fictitious eigenstrains," *Tribology International*, **82**, p.191-194, 2015.
[2] H. Wang, Z. Hu, W. Lu, and M.D. Thouless, "A mechanism-based framework for the numerical analysis of creep in zircaloy-4," *Journal of Nuclear Materials*, **433**, p.188-198, 2013.

Fretting mechanics: recent progress

Finite element modeling used to evaluate and refine design for new fretting tester under procurement



- 3-D FEA model using dynamic explicit code
- Rod and spring/dimple material: Zircaloy-4
- Rod modeled with length 356 mm
- Spring/two dimples modeled from scanned profile
- Contact defined between clad and spring/ dimples surfaces
- Initial velocity of clad upon impacting spring/dimples estimated as 0.25~0.62mm/s

Impact	FEA simulated reaction force (N)
Rod against spring	0.08 ~ 0.16
Rod against dimple	0.17 ~ 0.40

Used to define the specs of contact forces in bench tests.

New autoclave fretting-impact wear (AFIW) tester designed & in-fabrication

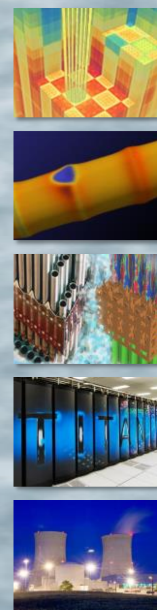
- First-ever bench tester to generate GTRF wear rate data in a realistic environment
- Results to be correlated with those of industrial dynamometer tests (cost >$100,000 per test)

Parameter	Impact + Fretting
Specimens	Actual rod and grid sections from WEC
Contact and motion	Fretting only, impact only, and fretting+impact
Pressure vessel size	Diameter < 4 inches
Water temperature	RT – 220 C
Fluid pressure	1 – 24 bars
Normal force (spring-loaded specimens)	0.1-1 N, calibrated by sensors prior to test
Tangential force	Measured during RT tests
Amplitude of oscillation	20 – 200 μm
Frequency	20 – 60 Hz
Inclined contact	adjustable angle

Video below shows the prototype providing desired motion.
Phoenix Tribology LTD, G . Plint

**Machine to be delivered in early 2016.*

Crud Challenge Problem Status



Science Council / Industry Council
November 4, 2015
Jeff Secker
Westinghouse Electric Co.

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Agenda

- Previous CASL Crud Accomplishments
- FY15 Crud Modeling Capabilities with VERA
- FY15 Level 1 Milestone Results
- FY16 Crud Plans

Crud Challenge Problem

Multi-Physics Needs for CIPS modeling

- A robust neutronics code is needed to accurately predict the core power (heat flux) distribution
- The neutronics model also needs to model the effect on the neutron flux and core reactivity as crud and boron are deposited
- A thermal-hydraulics model is needed to model the local thermal conditions in the core including the sub-cooled boiling distribution
- A crud deposition model is needed to grow the deposits during plant operation
- A crud chemistry model is needed to predict the concentration of B and Li in the crud and the precipitation of $Li_2B_4O_7$

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CASL Multi-physics tools for crud modeling

- The CASL MPACT 3D pin resolved transport code is used for the neutronics modeling
- The sub-channel thermal-hydraulics code, CTF, us used for the thermal-hydraulics modeling
- The CASL MAMBA code is used for the crud and chemistry modeling
- The three codes are coupled together to capture the deposition of crud, precipitation of boron in the crud, and the core response (flux, reactivity) to the deposition of the boron neutron absorber

CASL VERA for crud modeling

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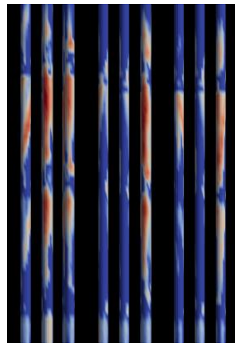
CRUD Risk Assessment

- CIPS
  - VERA tools provide direct method for CIPS evaluation
    - Improved crud/chemistry model
    - Advanced chemical thermodynamics
    - Address current methods lack of ability to accurately treat assemblies with power gradients or Gadolinia Burnable Absorbers
    - Fully coupled so all feedbacks treated consistently
- CILC
  - Targets enhanced Pressurized Water Reactor (PWR) Level IV crud risk assessment tools
- VERA tools and insights will be used to inform potential crud reducing strategies



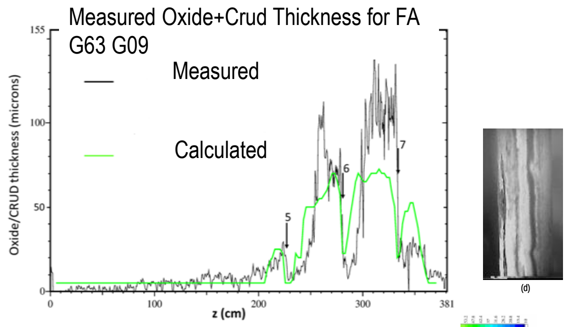
VERA will enhance crud risk assessment capability (Level III → IV)

CRUD Challenge Problem Phase 1 Successes

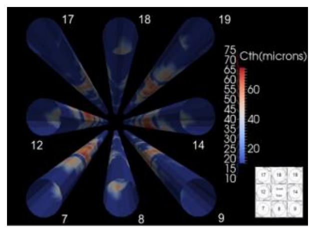
- ANC/VIPRE/BOA coupling
- MAMBA3D, MAMBA-BDM code developed
- STAR/MAMBA3D applied to Seabrook 5x5
- HYDRA/MAMBA1D applied to 3x3 rod array
- CTF/MAMBA1D applied to Seabrook 5x5
- Updated CTF/MAMBA1D applied to full Seabrook assembly
- MPACT updated to model crud and boron in the crud
- Quarter Core Analysis Completed for Watts Bar Unit 1 Cycles 5-7 (Cycle 7 experienced CIPS)

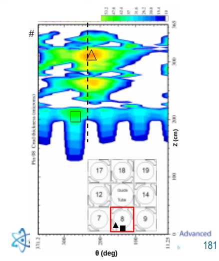
FY14 CIPS/CILC Simulation of Seabrook 1 Cycle 5 CRUD

- Seabrook Cycle 5 experienced both CIPS & CILC
- Validation exercise performed using MAMBA for simulated crud deposition event using 5x5 rod bundle
- Based on coupled CFD with CRUD



Planned for FY15 is crud predictions for an operating PWR based upon coupled neutronics + Thermal-hydraulics (subchannel) + CRUD model

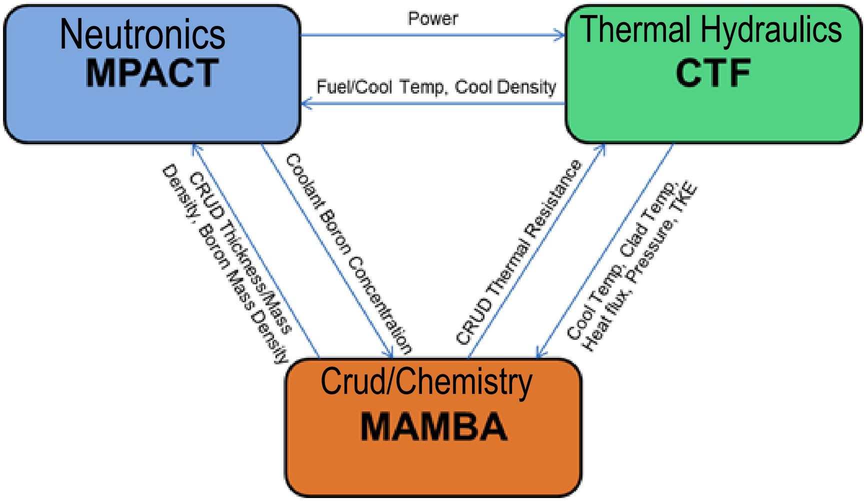




FY15 CRUD Challenge Problem Milestone Status

- L3.FMC.CRUD.P10.01, 12/31/2014 Distribution of MAMBA source code – Complete 2/24/15
- L3:PHI.CTF.P10.02, 5/15/15, Incorporate MAMBA into CTF – Complete
- L3:PHI.VCS.P11.01, 5/22/2015 Crud Coupling to MPACT – Complete
- L2:PHI.P11.01, 7/31/2015 VERA-CS for PWR Analysis of reactor steady state operation including multi-cycle capability and CIPS modeling capability – Complete
- L1:CASL.P11.03, 9/30/2015 Qualify Corewide PWR CIPS Capability w/ Corrosion Product Capability – Complete, but without corrosion product mass balance or fuel crud carryover

CASL Multi-physics tools for crud modeling



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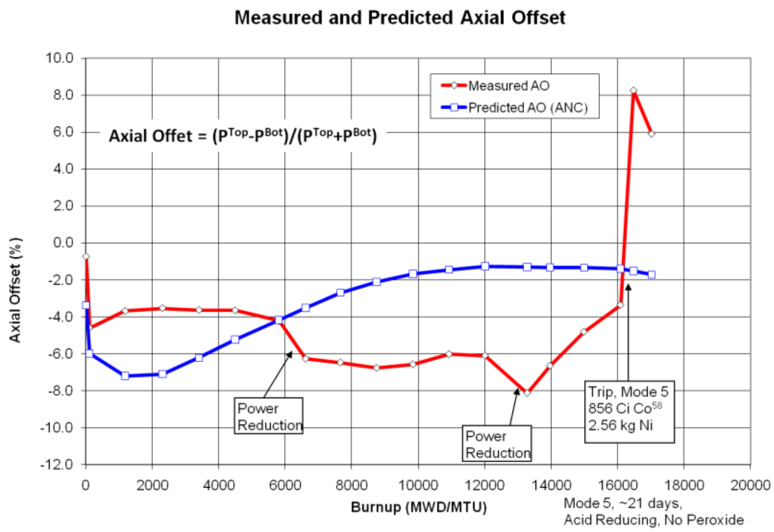
Watts Bar Unit 1 Cycle 7 CIPS



Cycle 7 Experienced CIPS

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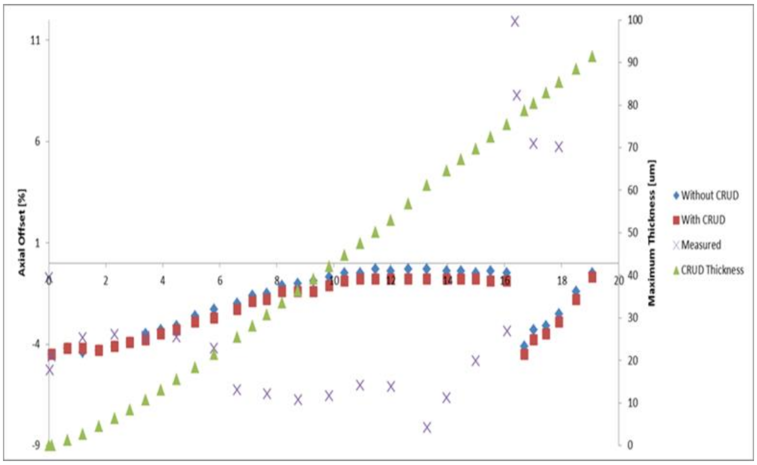
Watts Bar 1 Cycle 7
Initial MPACT/CTF/MAMBA1D Results



Initial Observations

- Too much crud on the core
  - 10X higher than BOA predictions
  - Low power assemblies still have 25-50% of the crud compared to high powered assemblies (Less than 10% in BOA)
  - Low powered assembly crud thickness is more than 50% of the high powered assemblies (less than 10% in BOA)
- Not enough boron deposition
  - 100X too low, despite 10X crud mass and 90 micron crud thickness

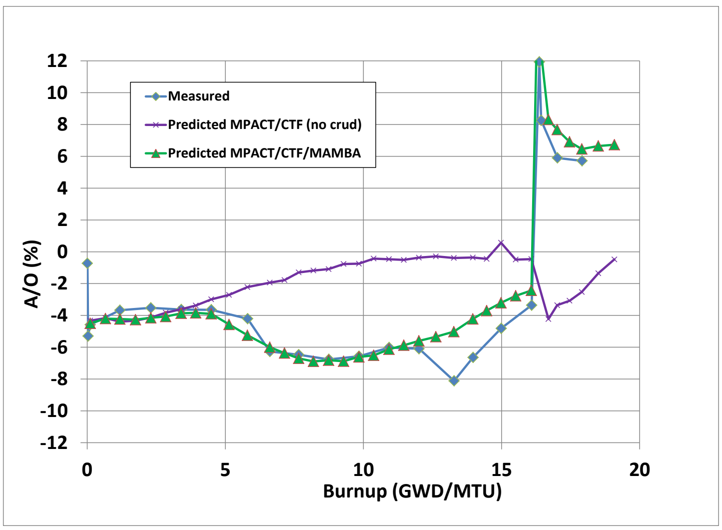
What is MAMBA missing?
How do we fix it?

Increasing Boron Mass in MAMBA

- MAMBA 3D was simplified to create MAMBA 1D
  - Heat transfer in radial direction only
  - Chemistry sub-routines replaced with simpler model to avoid Intellectual Property issues with MAMBA-1D release
  - MAMBA 1D development was benchmarked to previous results that used CFD based thermal-hydraulics rather than sub-channel T/H
- In MAMBA 1D, there is a threshold input below which boron won't precipitate. Currently the value is 0.005. This value can be decreased to increase boron mass
- There is also a parameter that sets the maximum boron in the crud. This is set to 16%. Increasing this will increase boron deposition.

2 inputs identified to increase boron mass

Updated Watts Bar 1 Cycle 7 Measured and Predicted Axial Offset Behavior

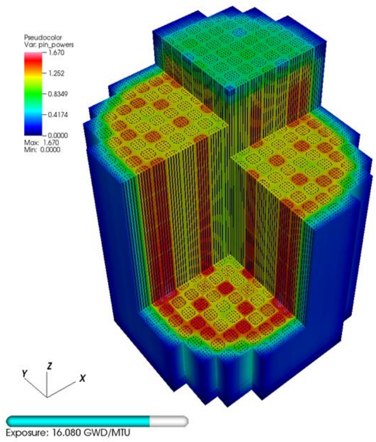


Concentration Threshold For Boron Precipitation Decreased 5X

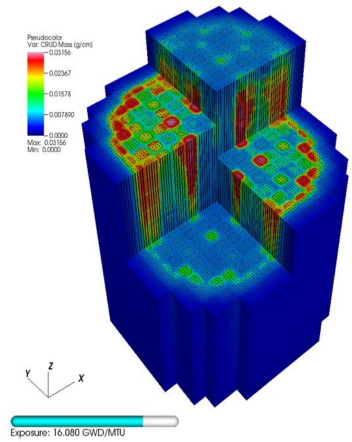
Fraction of Crud Available For Boron Deposition Increased 3X

Watts Bar 1 Cycle 7 Predicted Crud Distribution

Power Distribution

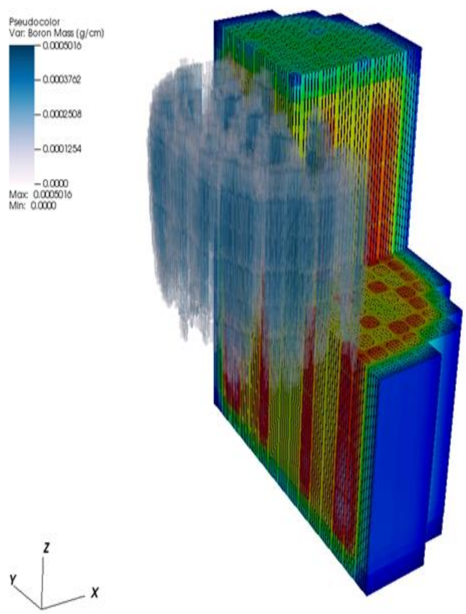


Crud Distribution



Watts Bar 1 Cycle 7 Predicted Boron Distribution

Boron Distribution at 16.08 GWD/MTU



Crud Mass Comparison

	MPACT/CTF/MAMBA							
	Crud Mass (lbm)							
	H	G	F	E	D	C	B	A
8	1.290	1.288	2.704	1.938	1.743	2.564	2.187	0.797
9	1.288	1.301	1.551	1.410	1.740	1.861	1.940	0.808
10	2.705	1.387	2.849	1.822	1.901	1.486	1.968	0.793
11	1.936	1.388	1.784	1.507	1.802	2.790	1.650	0.726
12	1.744	1.463	1.836	1.455	1.896	2.361	0.976	
13	2.564	1.988	1.528	2.749	2.395	1.426	0.741	
14	2.187	1.933	2.001	1.702	1.018	0.746		
15	0.797	0.791	0.799	0.733				
193 Assembly								
Total	314.1802							

	BOA							
	Crud Mass (lbm)							
	H	G	F	E	D	C	B	A
8	0.043	0.040	0.698	0.037	0.037	0.472	0.306	0.039
9	0.040	0.037	0.061	0.037	0.133	0.171	0.106	0.039
10	0.655	0.076	0.808	0.247	0.073	0.127	0.059	0.040
11	0.097	0.037	0.170	0.094	0.246	0.651	0.070	0.039
12	0.166	0.055	0.058	0.095	0.285	0.407	0.043	
13	0.477	0.114	0.086	0.553	0.389	0.037	0.039	
14	0.296	0.113	0.088	0.090	0.039	0.039		
15	0.039	0.039	0.039	0.039				
193 Assembly								
Total	30.70884							

Crud Thickness Comparison

	MPACT/CTF/MAMBA							
	Crud Thickness (mils)							
	H	G	F	E	D	C	B	A
8	1.03	1.06	2.56	2.46	2.44	2.22	2.36	0.48
9	1.06	0.94	1.80	1.56	2.49	2.52	2.14	0.48
10	2.56	1.40	2.64	2.34	1.93	1.67	2.44	0.48
11	2.46	1.55	2.44	1.36	2.19	2.51	2.35	0.45
12	2.44	1.44	1.86	1.60	2.31	2.50	0.61	
13	2.21	2.48	1.80	2.44	2.49	2.34	0.48	
14	2.36	2.15	2.47	2.41	0.66	0.49		
15	0.48	0.47	0.49	0.46				
			Location					
	Maximum	2.640	F-10					

	BOA							
	Crud Thickness (mils)							
	H	G	F	E	D	C	B	A
8	0.01	0.01	2.28	0.01	0.01	1.60	1.72	0.01
9	0.01	0.01	0.70	0.01	1.00	1.09	1.26	0.01
10	2.23	0.59	2.36	1.23	0.70	0.93	1.20	0.01
11	1.15	0.01	1.13	0.85	1.08	2.27	1.64	0.01
12	0.92	0.69	0.50	0.79	1.09	2.33	0.01	
13	1.61	1.22	0.87	2.12	2.26	0.01	0.01	
14	1.72	1.27	1.93	1.87	0.01	0.01		
15	0.01	0.01	0.01	0.01				
			Location					
	Maximum	2.360	F-10					

Boron Mass Comparison

MPACT/CTF/MAMBA

Boron Mass (lbm)

	H	G	F	E	D	C	B	A
8	0.000	0.000	0.023	0.009	0.005	0.015	0.011	0.000
9	0.000	0.000	0.002	0.000	0.004	0.006	0.007	0.000
10	0.023	0.000	0.026	0.006	0.002	0.000	0.010	0.000
11	0.009	0.000	0.005	0.002	0.006	0.024	0.006	0.000
12	0.005	0.001	0.001	0.001	0.009	0.017	0.000	
13	0.015	0.008	0.001	0.023	0.017	0.003	0.000	
14	0.011	0.007	0.011	0.007	0.000	0.000		
15	0.000	0.000	0.000	0.000				

193 Assembly

Total 1.09236

BOA

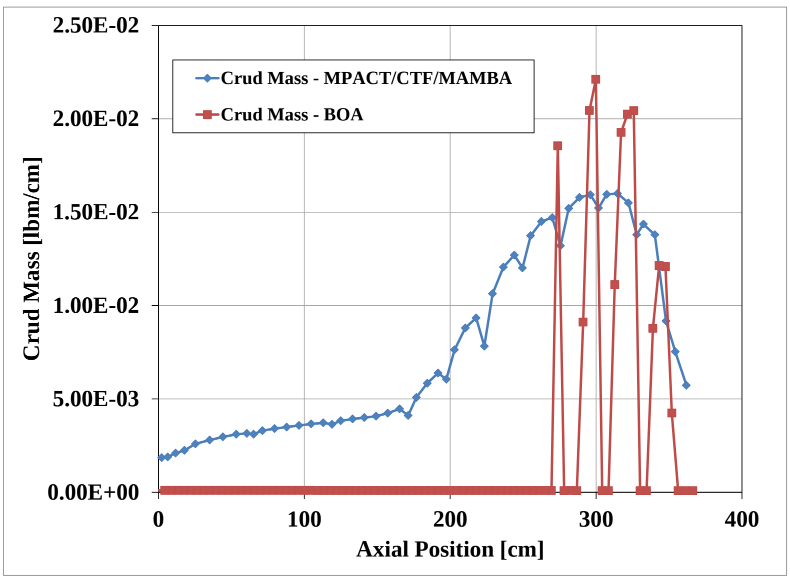
Boron Mass (lbm)

	H	G	F	E	D	C	B	A
8	0.000	0.000	0.031	0.000	0.000	0.009	0.009	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
10	0.028	0.000	0.037	0.000	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000	0.000	0.028	0.001	0.000
12	0.000	0.000	0.000	0.000	0.000	0.018	0.000	
13	0.009	0.000	0.000	0.022	0.016	0.000	0.000	
14	0.009	0.001	0.002	0.002	0.000	0.000		
15	0.000	0.000	0.000	0.000				

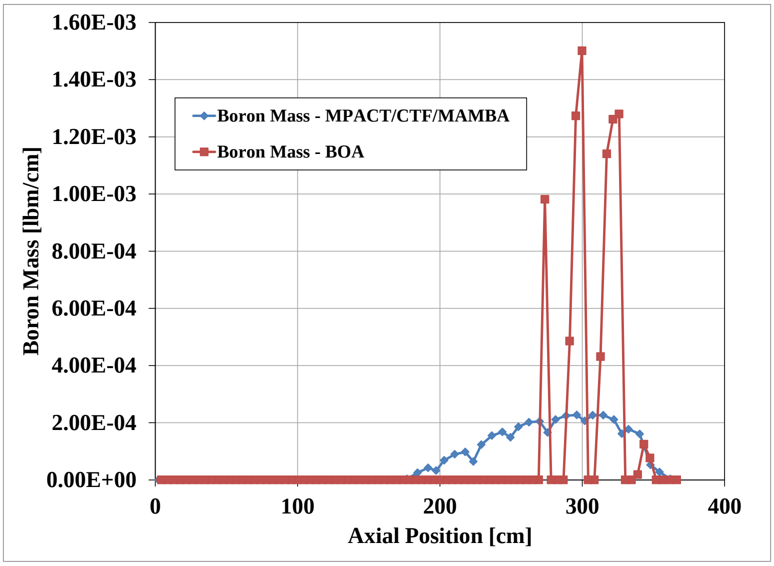
193 Assembly

Total 0.70412

Axial Crud Mass Distribution Comparison



Axial Boron Mass Distribution Comparison



CASL CIPS Modeling Conclusions

- CASL has developed multi-physics tools to model crud deposition on PWR cores and the resulting effects on core behavior
- Pin resolved 3D transport neutronics (MPACT) has been coupled with sub-channel thermal-hydraulics (CTF) and crud/chemistry models (MAMBA) to create a multi-physics crud modeling and simulation tool
- The CASL CIPS modeling tools accurately model the CIPS behavior experienced at Watts Bar Unit 1 Cycle 7
- Addition improvements to the models are planned and underway
  - Currently crud mass deposited is too large
  - Too much crud deposition in non-boiling areas of the core

CASL CIPS Challenge Problem

Future CIPS Modeling Improvements

- Compare MAMBA-3D results to MAMBA-1D results
  - What did we lose in fidelity?
- Compare CFD based and sub-channel based T-H models for their affect on MAMBA
- Implement Corrosion Product Mass Balance
  - Crud sources
    - Ongoing corrosion of piping and steam generator surfaces
    - Removal of crud from burned fuel and ex-core surfaces
  - Crud sinks
    - Deposition on fuel
    - Deposition in ex-core surfaces
    - Cleanup by Chemical Volume and Control System
- Implement fuel crud carryover and shuffling
- Implement B^{10} depletion for boron deposited in crud

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FY16 Plan for CRUD

- CIPS
  - Add corrosion product mass balance to models
    - Corrosion Product concentration is currently an input to the model
  - Validate CIPS predictions for at least two additional plants
    - Add corrosion produce mass balance model
    - Refine MAMBA as needed
    - Refine MPACT crud B10 depletion model as needed
  - Develop VUQ approach for MPACT/CTF/MAMBA
- CILC
  - Define boundary conditions for CFD from CIPS (CTF) models
  - Couple MAMBA with CFD tool (STAR-CCM+)
    - Investigating NEAMS/Argonne API for coupling STAR-CCM+ with MAMBA
  - Model Seabrook failed assemblies with CFD/MAMBA using CTF boundary conditions
  - Couple fuel performance corrosion model with CFD/MAMBA

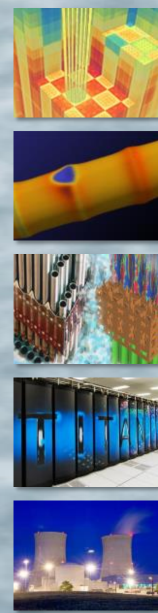
PCI Challenge Problem an Update

CASL Science / Industry Council Meeting
November 4-5, 2015
Oak Ridge National Laboratory

Presented by: *Joe Rashid*[1]

With Contributions from: *Nathan Capp[2], Wenfeng Liu[1], Ben Spencer[3], Carlos Tome'[4], Rich Williamson[3], and Brian Wirth[2] Mohammad Zikry[5]*

[1] ANATECH-SI
[2] University of Tennessee Knoxville
[3] Idaho National Laboratory
[4] Los Alamos National Laboratory
[5] North Carolina State University



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Outline

- The Anatomy of PCI
- Recent Progress
- Future Work

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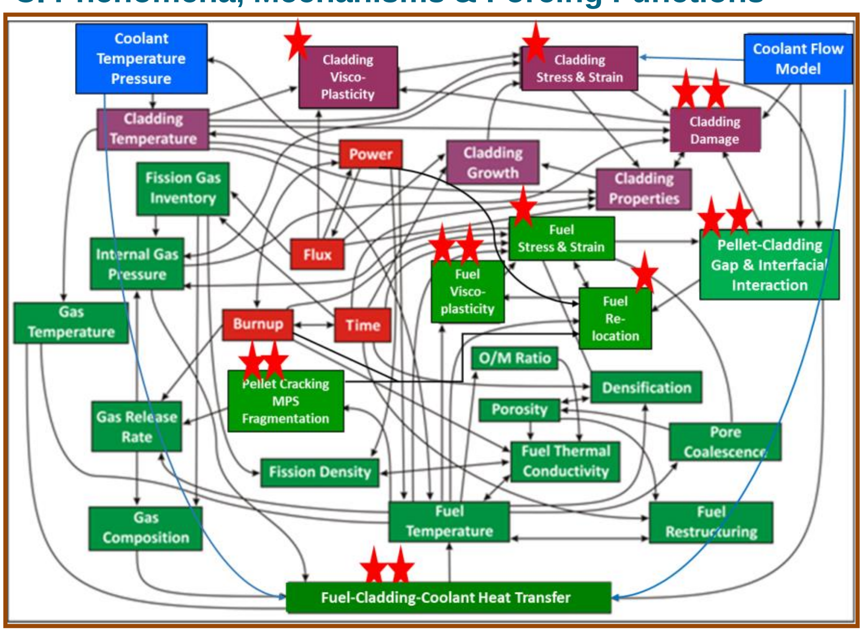
The Anatomy of PCI, and Why is it still so Challenging after four decades of work?

A possible explanation may lie in the following slide

PCI Phenomena, Mechanisms & Forcing Functions

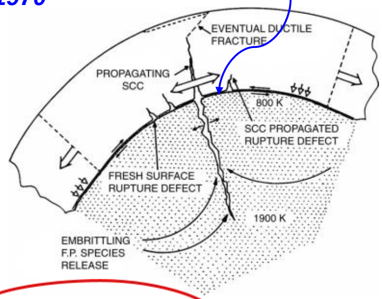


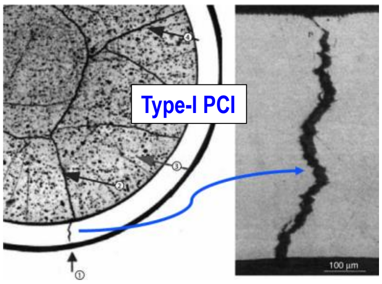
Pellet-Clad Interaction (PCI) Mechanism

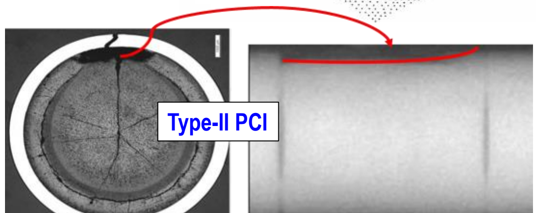
- Type-I: SCC-PCI – ***Began to appear in BWRs ~ 1970***
- Type-II. MPS-assisted (MPS-PCI) ***~ 2003***
- **Pellet Crack is a common feature for both**
- **Cladding multi-stage failure evolution**
  - Crack initiation: Time-to-Failure t_f, CDI
  - Crack extension: $K_I \geq K_{ISCC}$, K_{IH}
  - Mechanical rupture by ***SED ≥ CSED***

F(T, φt, H)

Interaction layer at H Bu bonds fuel to clad







Aleshin et. al., Westinghouse, TopFuel 2010

Recent Progress

- Part 1: Model Development and/or Improvement
- Part 2: Application to PCI analysis of commercial fuel – Demonstration of Code capabilities

Part 1: Model Development and/or Improvement

- **Fuel relocation model**: Made user independent, but still empirical
- **Gd thermal conductivity model**: Corrected known low-burnup anomalies
- **IFBA model implementation**: (ongoing)
- **Corrosion models from Falcon**: Implement code changes to enable use of Fortran subroutines, (ongoing)
- **UO_2 hot-pressing model (compressible visco-plasticity)**: (ongoing)
- **Smeared cracking model is progressing slowly**: works well in a single element debug problem, but has convergence difficulties in application problems
- **Fuel-cladding contact – Recent Improvements:**

  Next slide

Fuel-Clad Gap Thermo-Mechanics is the Achilles Heal for Fuel Performance Codes

- Gap conductance is highly dependent on the mechanical response
  - Requires highly complex contact algorithm
  - Historically, is the source of convergence problems in BISON
    - If a model didn't converge, contact was usually blamed first.
  - New contact enforcement system developed starting in mid-2014
  - Significant improvements have been made with CASL funding.
  - Robustness of glued and frictionless contact is rarely an issue now.
  - Significant improvement in frictional contact
    - Ongoing work to further improve frictional contact

Part 2: Application to commercial fuel Rods

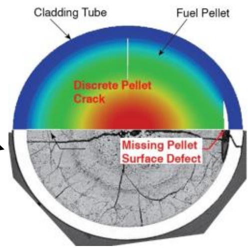
- Field observations: Provides ample material for Code benchmarking and V&V
  - **Confirmed PCI:**
    - **BWRs**: Hope Creek, KKL, LaSalle, Hatch, and Kuosheng
    - **PWRs**: Braidwood 1 and 2 , Byron, Watts Bar, Crystal River 3, Oconee 2
      - **Type-I PCI-SCC**: Braidwood 1, Crystal River 3
      - **Type-II PCI-MPS:** Braidwood 2, Byron 1, Oconee 2 *suspected)*.
  - **Suspected PCI:**
    - **BWRs:** Browns Ferry 3, J.A. FitzPatrick, Grand Gulf, Oyster Creek, Quad Cities.
    - **PWRs**: Byron 1, Crystal River 3, Oconee 2, TMI 1, Watts Bar
      - **Type-II PCI-MPS:** Oconee 2

PCI analysis of PWR rods: Demonstration of Code capabilities for:

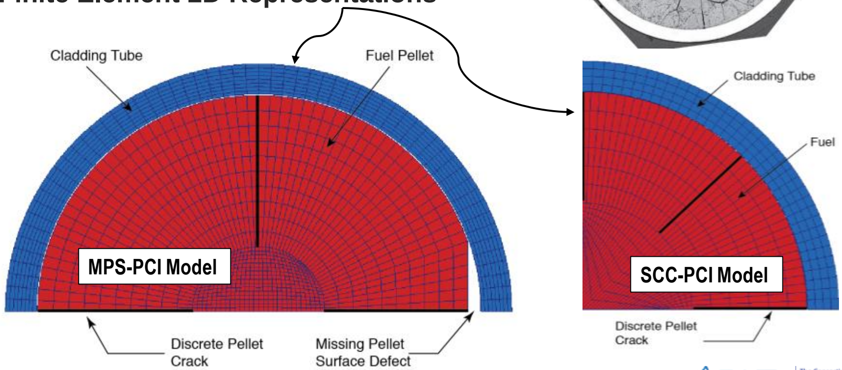
- SCC-PCI versus MPS-PCI
  - Narrow-angle versus wide-angle MPS
- Separating failures from no-failures
  - 3D versus 2D
  - 2D Falcon (Industry Code) versus 2D/3D BISON
- Contact Conditions at Pellet-Cladding Interface
  - Friction vs. Bonding

PCI analysis of PWR rods: Demonstration of Code capabilities: *SCC-PCI vs. MPS-PCI*

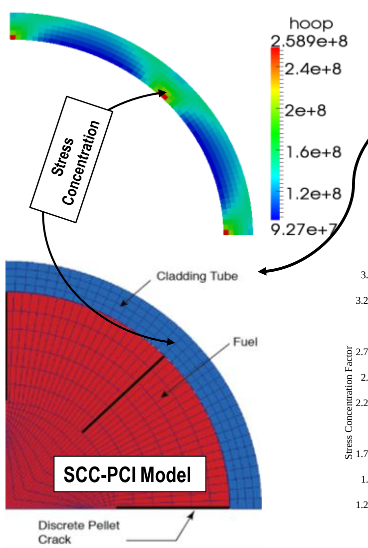
- **Typical MPS cross-section**

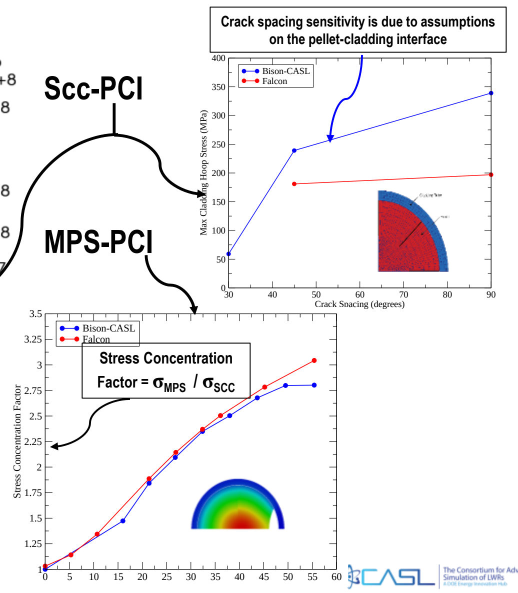


- **Finite Element 2D Representations**

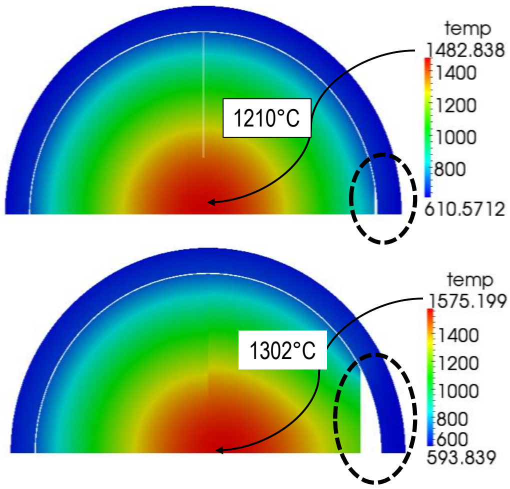


PCI analysis of PWR rods: Demonstration of Code capabilities: *SCC-PCI vs. MPS-PCI*





PCI analysis of PWR rods: Demonstration of Code capabilities: *MPS size*



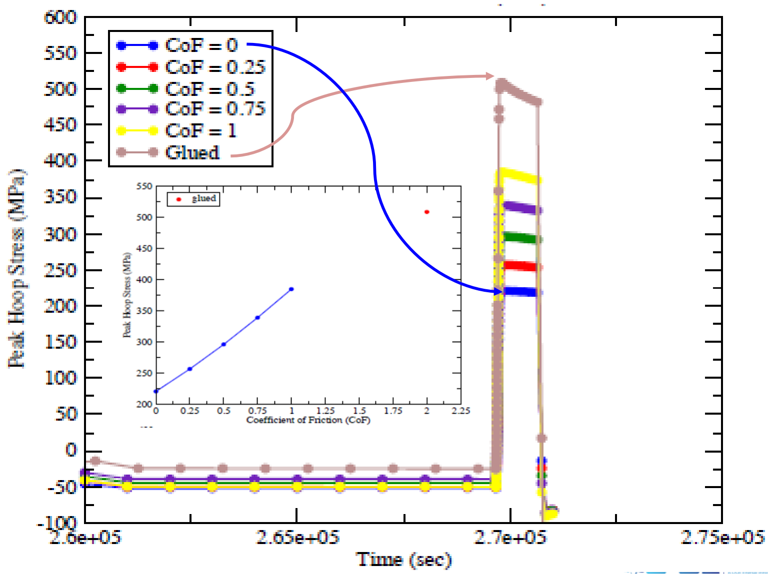
PCI analysis of PWR rods: Demonstration of Code capabilities: Failures / no-failures

2-D & 3-D Braidwood PCI and MPS Results

		Burnup (MWd/tU)	R-Z Peak Stress	PCI Peak Stress	PCI SED	60mil Peak Stress	60mil SED	125mil Peak Stress	125mil SED
M16S_O05 (F)	2D	20.7	77	335	.894	537	1.67	685	6.85
	3D		77	262	0.520	391	1.01	526	1.7
M16S_O04 (NF)	2D	19.6	14	274	.613	459	1.22		
	3D		14	173	0.249	314	0.723		

Ramp Tests	W4---1 (F)	W4---2 (NF)	W5---4 (NF)	W5---5 (NF)	W5---6 (F)
Rod Avg Burnup (MWd/tU)	19.02	19.07	15.25	20.7	20.7
Bison---CASL R---Z (MPa)	93	75.2	30.3	112	140
Bison---CASL 2D (CoF = 0.75) (MPa)	437	330	181	525	529
Bison---CASL (SED in MJ)	1.45	.862	.332	2.03	2.09
Bison---CASL 3D (Mpa)	348	160	10	371	420
Bison---CASL 3D (SED in MJ)	1	.359	.036	1.15	1.64
Falcon (MPa)	N/A	N/A	291.8	453.2	474.2

PCI analysis of PWR rods: Demonstration of Code capabilities: Fuel-Clad Contact Friction vs. Bond



Future Work

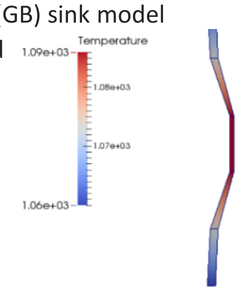
- Towards the development of a User Tolerant Predictive Code
- Mechanistic behavior through lower-scale material modeling
  - Microstructural modeling of cladding viscoplasticity, *Tome' et.al.*
  - Microstructural modeling of cladding fracture *Zikry et.al.*
  - Multi-Phase Damage Model for Zr-4 Cladding *Rashid et.al.*
- Discrete Fracture Modeling
- Plan for BWR PCI Methodology

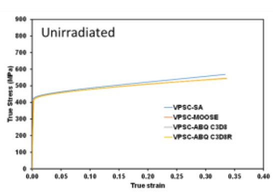
Towards the development of a User Tolerant Predictive Code

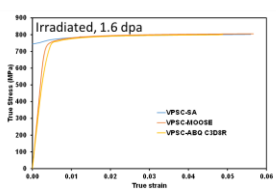
- User Tolerant Code
  - Robust Numerics – Immune from convergence failures
  - Does not depend on the user's expert knowledge of the Code
  - Well equipped with user-convenient features for processing results
- Add additional capabilities to make the Code a predictive tool instead of just explaining observations – Needed to meet set milestones
  - Major elements:
    - Apply frictional contact to PCMI problems (r-θ models)
    - Use XFEM to represent discrete fractures in PCMI problems
    - Expand the Code's Benchmarking and V&V Database
    - Develop high fidelity cladding failure measures stated on Slide 5.
    - Introduce lower-scale material models for mechanistic behavior
- Plan for BWR PCI Methodology

Mechanistic behavior through lower-scale material constitutive modeling

- Visco-Plastic Self-Consistent (VPSC) polycrystal plasticity model for large-strain deformation
  - Irradiation growth model with grain boundary (GB) sink model
  - Only 50 grains with random texture are needed to simulate material constitutive behavior
  - Model is implemented in BISON
  - Application: Cladding Ballooning in LOCA



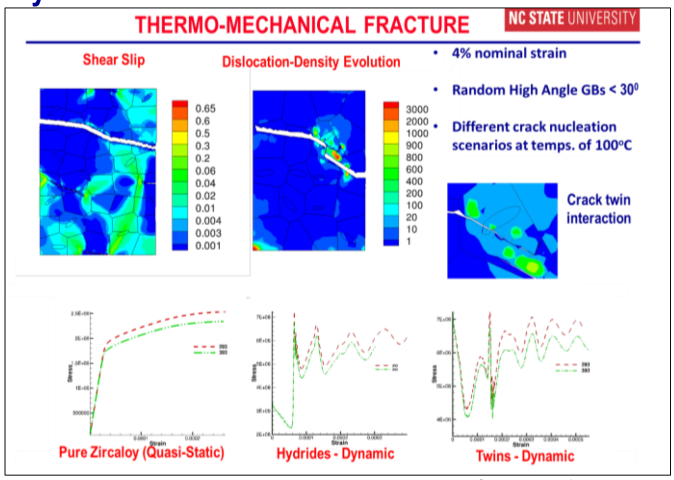




Mechanistic behavior through lower-scale material constitutive modeling

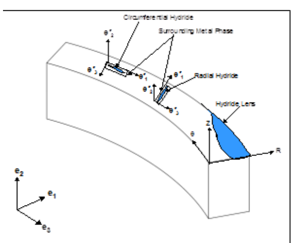
- **Microstructural Modeling of Intergranular and Transgranular Fracture in Zircaloys**

  - Work in progress
  - Potential Application to Cladding with typical hydride structure
  - To be compared with the 3-phase damage model (*Next Slide*)

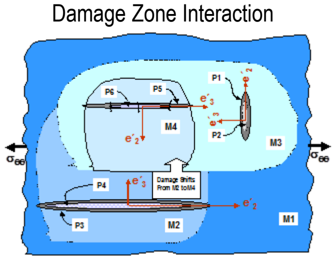


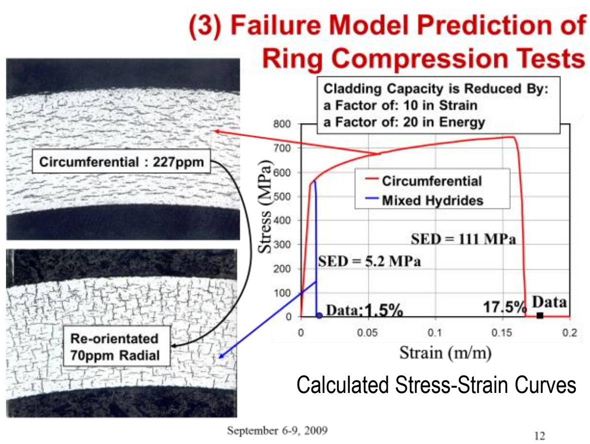
Multi-Phase Damage Model for Zr-4 Cladding: **Metal, Circumf. Hydrides, Radial, Hydrides, Hydride Lens**

Material Phases



Damage Zone Interaction

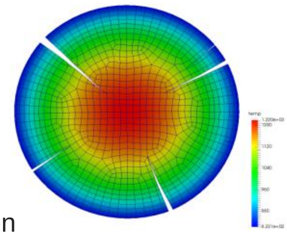


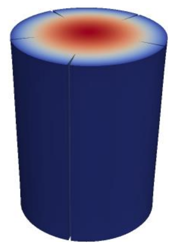


Calculated Stress-Strain Curves

Future work: *Discrete Fracture Modeling*

- 3-year LDRD project just completed at INL to develop and apply advanced fracture methods to fuel fracture
- XFEM was one of methods pursued
  - Enriches standard continuous FEM basis functions with discontinuities
  - Permits arbitrary, mesh-independent propagation of discrete fractures
  - Developed in MOOSE/BISON, demonstrated for 2D crack propagation, 3D stationary cracks
- INL has FY16 CASL milestones to apply XFEM to represent the effects of fractures at fuel/cladding interface for PCMI problems.





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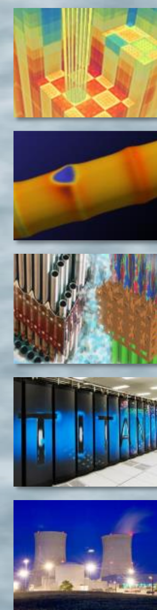
Progress on DNB Challenge Problem



Yixing Sung
DNB Challenge Problem Integrator

November 4, 2015
Joint Industry Council/Science Council Meeting

The Consortium for Advanced Simulation of LWRs
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DNB Challenge Problem Progress

- Review of Challenge Problem
- CASL Path Forward
- FY15 Completed Work
- Work in Progress in FY16
- Phase 2 Milestones
- Summary

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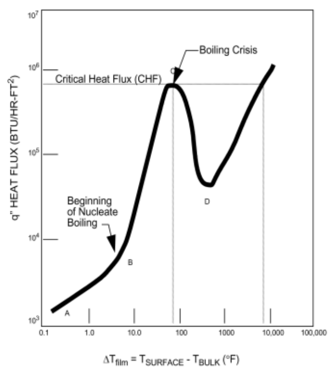
Departure from Nucleate Boiling (DNB)

- DNB also referred to as Critical Heat Flux (CHF)
- Local clad surface dryout causes dramatic reduction in heat transfer during transients (e.g., overpower and loss of coolant flow)
- One of safety and regulatory acceptance criteria for PWR (DNB) and BWR (dryout)
- CASL objectives and path forward defined in Charter and Implementation Plan
  - Focus on PWR (DNB) first

Boiling Curve



CASL Path Forward – Focus on Modeling & Simulation (M&S) Needs for Industry

- Fuel hardware design improvement (CFD)
  - Higher fidelity of M&S capabilities (multi-phase) to predict fluid and fuel surface conditions and effects of fuel design features (e.g., grid spacer)
  - Applications of advanced data assimilation and uncertainty quantification methods on test design, data collection and analysis
  - Control and optimization of fuel cladding surface morphology and properties during reactor operation
- Margin quantification in accident analysis (VERA-CS)
  - Multi-scale and multi-physics M&S capabilities
  - Technical basis for DNB-related fuel failure (e.g., DNB during Reactivity Insertion Accident (RIA))

FY15 Activities – DNB CP

Milestones

- Apply coupled VERA-CS code and CFD tool to PWR HZP SLB cases (VMA / PHI)
  - High flow case (with offsite power)
  - Low flow case (without offsite power) and case comparisons
- R&D on CFD two-phase flow CLS
- CFD modeling of 5x5 rod bundle mixing test

Difficulties

- Adequacy of CFD modeling for core inlet flow and temperature distributions
- VUQ method application
- Computing resource required for VERA-CS run

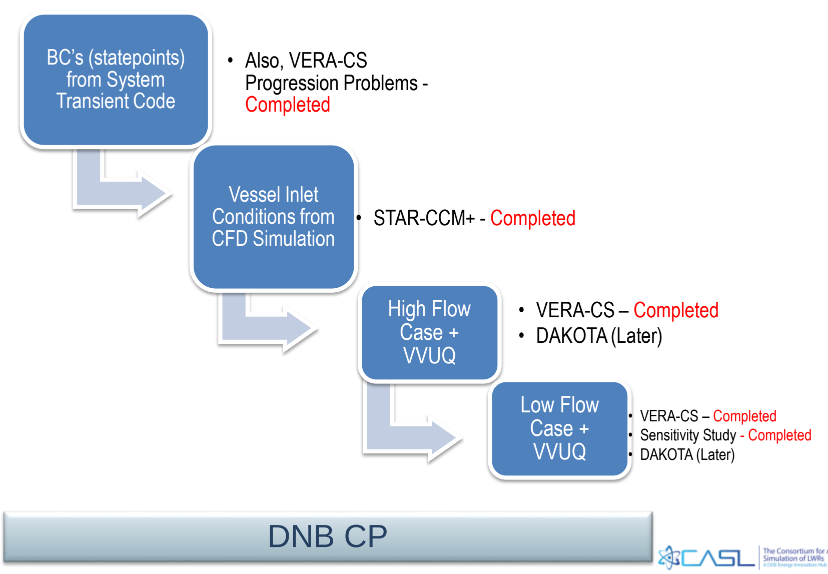
Successes

- High and low flow CFD core inlet boundary conditions using STAR-CCM+
- VERA-CS capable of simulating both high and flow cases on Titan
- Improving CTF for DNBR (e.g., Tong factor)
- Preliminary results show low flow case less DNB limiting than high flow case

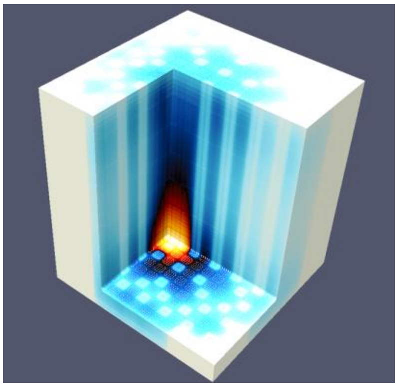
Course Corrections

- Stop work on Hydra-TH application
- Sensitivity studies:
  - Downstream effect on CFD predicted core inlet condition through porous media option
  - Effect of CFD results on VERA-CS and DNBR results
- Will define VUQ objective and approach in FY16
- Update DNB CP implementation plan in FY16

FY15 DNB CP SLB Cases – Work Flow

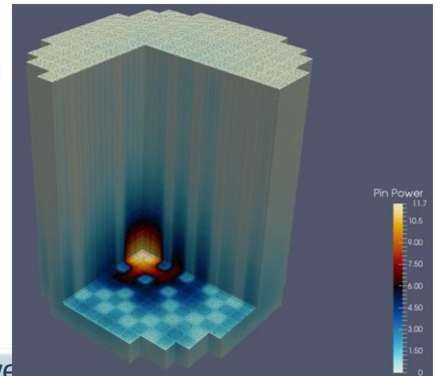


DNB CP HZP SLB Case Study



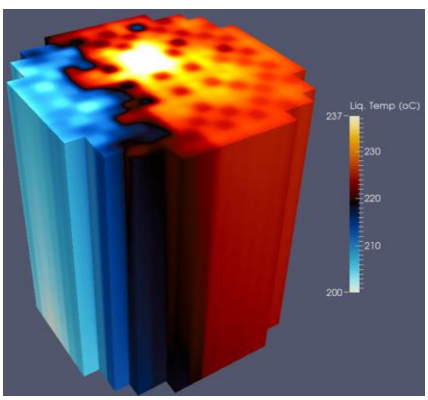
High Flow Case

Low Flow Case



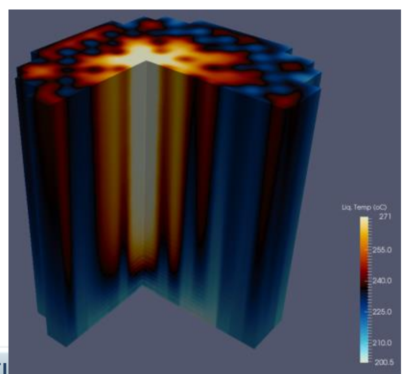
Core Pin Powe

DNB CP HZP SLB Case Study



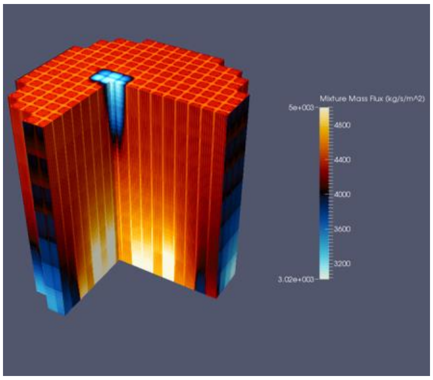
High Flow Case

Low Flow Case



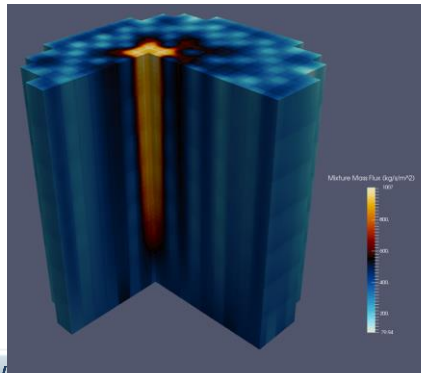
Core Fluid Temperatu

DNB CP HZP SLB Case Study



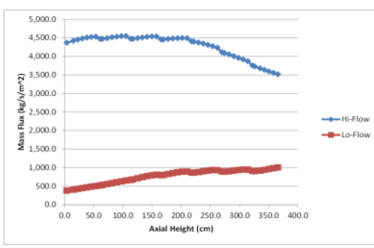
High Flow Case

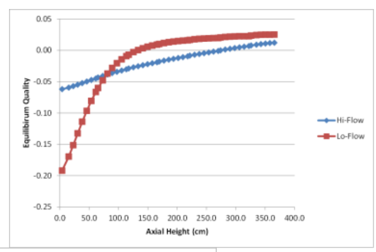
Low Flow Case

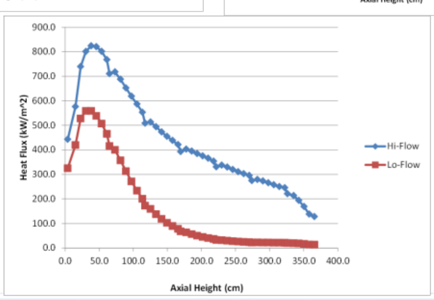


Core Mass Flow Distributions

DNB CP HZP SLB Case Study







Hot Channel Parameter Comparisons

FY16 Activities

- L2:THM.P13.01, “Demonstrate DNB Analysis Methods Using CFD for Non-Mixing Vane and V5H Grid Spacers”
  - Data support from VMA
  - Method development by THM
- L3:VMA.P14.xx, “UQ Approach Study Using Dakota”
  - Follow-up SLB high and low flow case study
- L3:VMA.P14.xx, Hi2Lo Application based on STAR-CCM+ (CFD) and CTF (subchannel) single phase mixing and/or heat transfer
- L3:VMA.P14.xx, “DNB CP Implementation Plan Update”
- Data collection and transmittal to CASL
  - PWR MV Grid rod bundle test data

Phase 2 Plan beyond FY16

- Qualify prediction of onset of DNB using M-CFD (FY17)
- Evaluate and apply enhanced VERA-CS to DNB limiting transients (FY18)
- Demonstrate prediction of onset of DNB (CHF) using M-CFD for low flow conditions (FY19)

- Pursue complete success of Desirable Level and Ultimate End Game in Phase 2
  - Coupled VERA-CS code system with kinetic and VUQ capabilities
  - Application of multi-physics and high fidelity modeling and simulation and VUQ capabilities to resolve DNBR margin pre

DNB CP

Summary

- CASL DNB CP approach based on multi-scale and multi-physics modeling and simulations to meet industry's needs
  - CFD for fuel design feature improvements
  - VERA-CS for reactor core response and margin quantification
- Phase 2 work in progress based on Phase 1 accomplishments
  - Performed steady state VERA-CS application to SLB cases in FY15
  - Continue R&D on high resolution (CFD) DNB modeling
  - DNB CP implementation plan to be updated (more emphasis on UQ approach and process)

DNB CP

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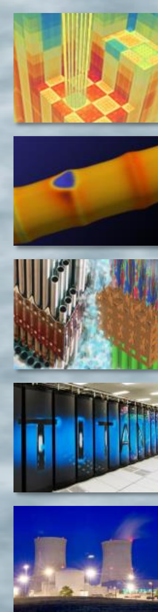
Progress on LOCA & RIA Challenge Problems

Gregg Swindlehurst
LOCA & RIA Challenge Problem Integrator

November 4, 2015
Joint Industry Council/Science Council Meeting



CASL The Consortium for Advanced Simulation of LWRs A DOE Energy Innovation Hub

U.S. DEPARTMENT OF ENERGY

LOCA & RIA Challenge Problems Goal

CASL goal is a higher fidelity simulation of the fuel rod response during LOCA, and the reactor and fuel rod response during RIA, to achieve the following

- Obtain better understanding of the physics (advance the science and understand/respond to emerging research results)
- Reduce conservatism in the industry analytical methods (gain margin)
- Inform the regulatory process (minimize impact of changes / avoid high cost of testing)
- Support power uprates and fuel and reload design (design and economic optimization)

LOCA and RIA CP Value Proposition

LOCA Research Results

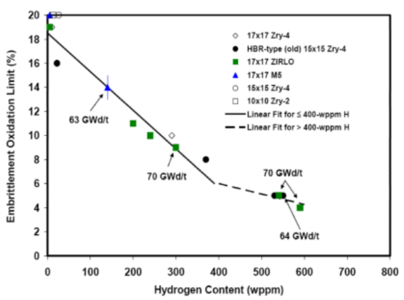
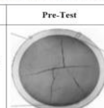
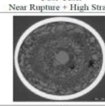
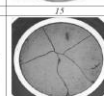
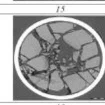
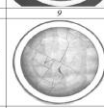
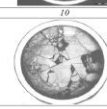


Figure 1. Ductile-to-brittle transition oxidation level (CP-ECR) as a function of pretest hydrogen content in cladding metal for as-fabricated, prehydrided, and high-burnup cladding materials. Samples were oxidized at ≤1,200 °C ±10 °C and quenched at 800 °C. For high-burnup cladding with about 550-wppm hydrogen, embrittlement occurred during the heating ramp at 1,160–1,180 °C peak oxidation temperatures (Ref. 8).

Cladding Embrittlement At Higher Burnup (Ref. RG 1.224)

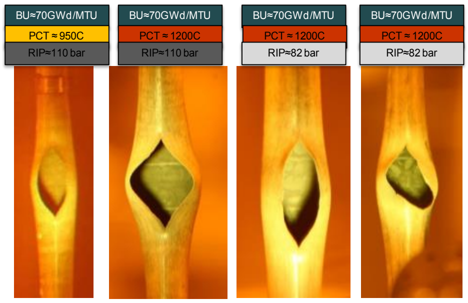
Fuel Fragmentation At Higher Burnup (Ref. NRC - TopFuel 2013)

Table 1. Characterization of fuel fragmentation before and after integral LOCA testing

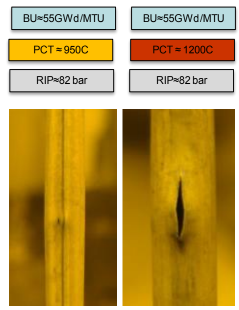
Test/ Laboratory	Segment	Pre-Test	Post-Test: Near Rupture + High Strain
IFA-650.5, Halden	83 GWd/MTU PWR rod		
Reference		*15*	*15*
IFA-650.7, Halden	44 GWd/MTU BWR rod		
Reference		*9*	*10*
ICL#2, ANL	56 GWd/MTU BWR rod		

Degraded LOCA Performance at Higher Burnup

LOCA Research Results



Rupture opening in Studsvik LOCA tests 189, 191, 192, and 193 (left to right), showing the absence of fuel in the rupture plane.



Rupture opening in Studsvik LOCA tests 196 and 198 (left to right)

Higher Burnup Effects

- Higher strain (ballooning)
- Larger burst opening
- More fuel fragmentation and relocation
- More fuel dispersal

Adverse Cladding Rupture and Fuel Dispersal Phenomena

LOCA Regulatory Changes

- NRC will issue 50.46c in 2016

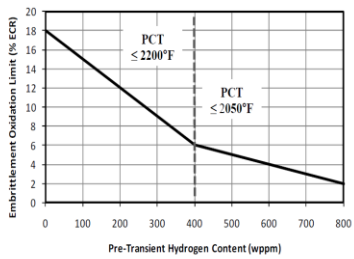


Figure 2. An acceptable analytical limit on peak cladding temperature and integral time at temperature (as calculated in local oxidation calculations using the CP correlation (Ref. 11))

17% cladding oxidation limit and PCT reduced with burnup (RG 1.224)

- Fuel fragmentation, relocation, and dispersal are not in the 50.46c rule (research continuing and regulatory position evolving)
- License amendment requests for higher burnup are on hold

LOCA CP Status

- Charter and Implementation Plan completed (living documents)
- Completed development activities
  - Demonstration of BISON-CASL using WEC LOCA code boundary conditions
- Current state of BISON-CASL LOCA capabilities captured in INL TopFuel 2015 paper "Modelling of Fuel Behaviour During Loss-of-Coolant Accidents Using the BISON Code"
- LOCA CP planning meeting 8/11/2015
  - Discussion and decisions on detailed scope
    - Fuel dispersal not in scope
  - Need for and expansion of BISON-CASL LOCA modeling capabilities
  - Need for multi-rod modeling discussed
  - Coupling options discussed

LOCA CP Challenges

- CASL scope is not fully integrated LOCA modeling, so entity using BISON-CASL will require their own LOCA system T/H capability to drive it
- CASL will need access to high-profile validation data (Halden, Studsvik, etc.)
- Axial fuel relocation modeling not currently in scope
- Fuel dispersion will not be in scope
- Multi-rod capability (unknown if NRC will require it)
- Vendor proprietary fuel properties and test data
- International codes and modeling capabilities

LOCA CP Opportunities

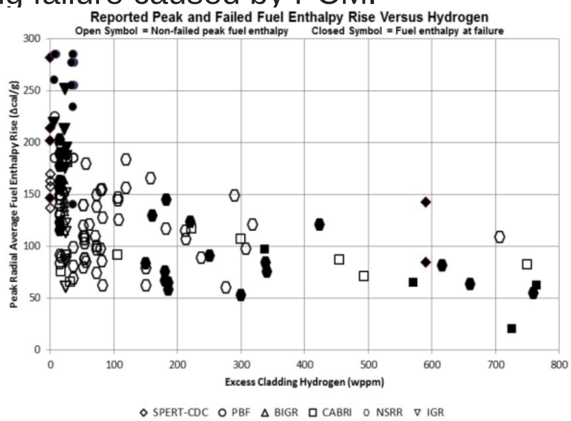
- First-of-a-kind modeling and simulation of fuel pellet and cladding phenomena resulting from higher burnup
- Limited and sometimes conflicting data and no industry consensus on behaviors
- Indications of local effects
- Indications that the power history affects the fuel rod performance during a LOCA
- ID oxidation not modeled by industry (regulatory compliance plan is to simply double OD oxidation)
- Fragmentation not included in 50.46c rule (time for CASL to contribute)

LOCA CP Milestones

- FY18 L1 – PWR LOCA fuel performance capability
- FY19 L2 – PWR LOCA VVUQ
- FY20 L1 – BWR LOCA fuel performance capability

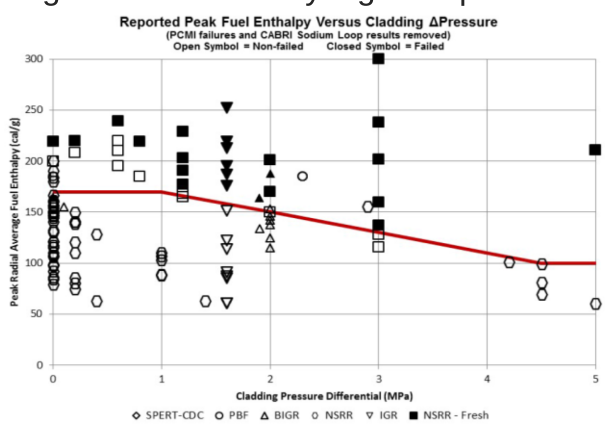
RIA Research Results

RIA fuel rod tests with higher burnup have shown reduced capability to survive power excursions due to cladding failure caused by PCMI



RIA Research Results

RIA fuel rod tests with higher burnup have shown reduced capability to survive power excursions due to cladding failure caused by high temperature



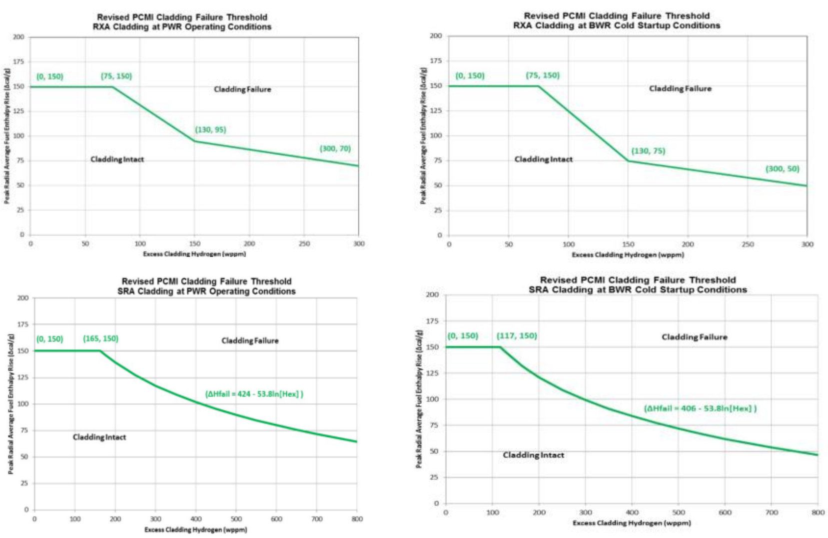
RIA Regulatory Changes

March 16, 2015 NRC memo (ADAMS ML14188C423)

- Proposed changes to SRP 4.2 Appendix B (2007) based on additional research (including 43 NSRR tests with corrected results)
- PCMI limits separated based on cladding material fabrication process
  - SRA = stress-relief-annealed (Zircaloy-4, ZIRLO™)
  - RXA = recrystallized (Zircaloy-2, M5, Optimized-ZIRLO™)
- Zero initial power high-temperature cladding failure limit based on cladding pressure differential
- No credit for atypical RIA pulse and test temperature effects
- Limited incipient melting allowed at pellet centerline

  - ➢ Not yet known to what extent fuel design or reload design or operation will be impacted
  - ➢ Compliance implementation expected on a forward-fit basis

RIA Regulatory Changes



Lower RIA Regulatory Limits at Higher Burnup

RIA CP Status

- Charter and Implementation Plan completed (living documents)
- Completed development activities
  - Initial MPACT modeling of SPERT RIA tests
  - Initial CASL-BISON modeling of PWR fuel rod response to RIA
  - Initial CTF modeling of NSRR RIA fuel rod test
  - Initial CTF modeling of PWR whole core rod ejection
- RIA CP planning meeting will he held to finalize detailed scope

RIA CP Challenges/Opportunities

- Computer resources for whole core pin-resolved transient RIA simulation
- CASL access to CABRI and NSRR RIA test data
- Simulation of CHF, post-CHF, and rewetting modeling with limited prototypical PWR transient RIA data
- Future CABRI water loop RIA tests
  - Ten tests beginning in 2016

RIA CP Milestones

- FY16 L2: FMC.P13.02 BISON capabilities for RIA
- FY16 L2: RTM.P13.03 Transient Neutronics with Feedback: Implementation of transient capability with internal heat conduction feedback in MPACT for PWRs
- FY18 L1 – Demonstrate core-wide PWR rod ejection accident
- FY19 L1 – Demonstrate core-wide BWR rod drop accident

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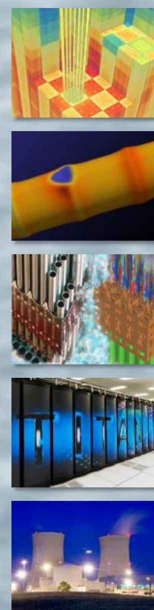
BWR Simulation Progress: CTF and MPACT



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Overview of Presentation

- Initial BWR Capability in MPACT
- BWR Validation in CTF
- Conclusion and Future Work

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CASL BWR Plans for Phase 2

- CASL Phase 2 Goal for BWRs is a core subregion (e.g. control cell)
  - Allows us to demonstrate multiphysics coupling at BWR conditions
- Stretch goal is a full-core
  - Full-core analysis with bypass and recirculation loops is prohibitive

Initial BWR Capability in MPACT

Completed milestone to develop initial capability:

- Milestone L2:RTM.P10.01 (DOE Reportable)
- Kochunas, B., D. Jabaay, A. Fitzgerald and T. Downar, S. Palmtag, "Initial BWR Modeling Capability for MPACT", CASL Technical Report: CASL-U-2015-0265-000, July 31, 2015.

  http://www.casl.gov/docs/CASL-U-2015-0265-000.pdf

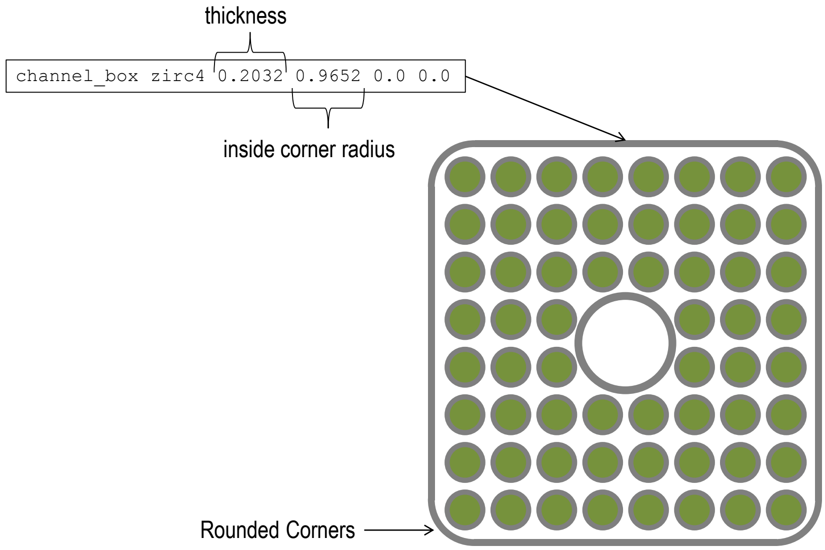
Initial BWR Capability in MPACT

- Primary Goals (Peach Bottom Designs+)
  - Channel box with rounded corners
  - Wide and narrow gaps on outside of channel box
  - Ability to specify different void/density inside and outside channel box
  - GE Original Equipment Manufacturer (OEM) control blade design
  - Large water rods that occupy 2x2 pin cells
- Secondary Goals (Proprietary Designs)
  - Thick channel box corners
  - Square water rods (e.g. ATRIUM designs)
  - GE-11 and GE-9 designs
- Not supporting:
  - SVEA's, thick-thin channel boxes, diagonal symmetry, detectors, mixed configurations

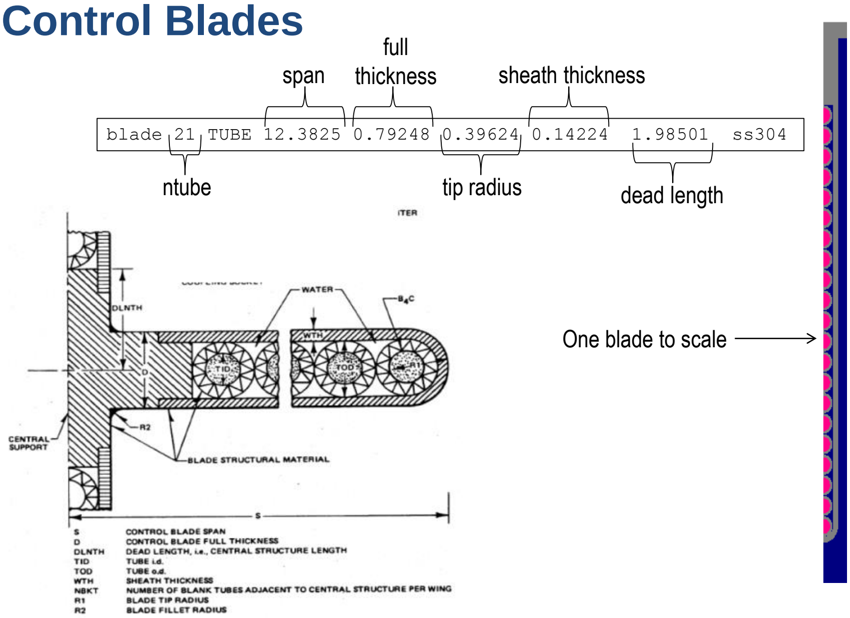
BWR Modeling Capability in MPACT

- All work involved modifications to:
  - Input processor
  - Geometry and mesh representation
  - Edit capabilities
- New input processing features
  - Reactor_type [BWR,PWR]
  - Wide and narrow gap
  - Channel box
  - Control blade
  - Large water rods
  - 2-D assembly void maps
- **No Changes to the Solvers**

Channel Boxes

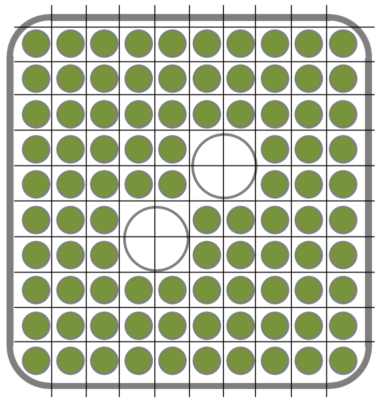


Control Blades



Large Water Rods

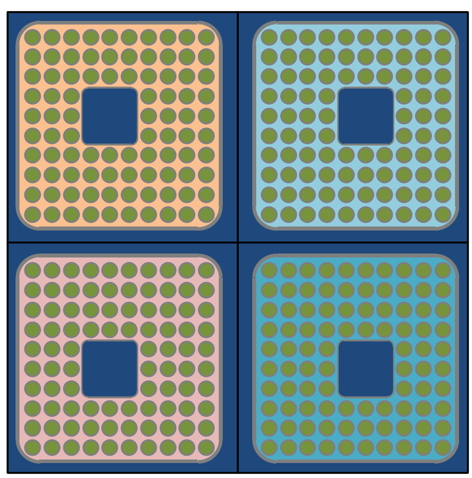
```
ppitch 1.295
cell WR 1.26 1.28 / mod zirc4 / large4

lattice LAT
     1
     1  1
     1  1  1
     1  1  1  1
     1  1  1  1  1
     1  1  1 WR WR  1
     1  1  1 WR WR  1  1
     1  1  1  1  1  1  1  1
     1  1  1  1  1  1  1  1  1
     1  1  1  1  1  1  1  1  1  1
```



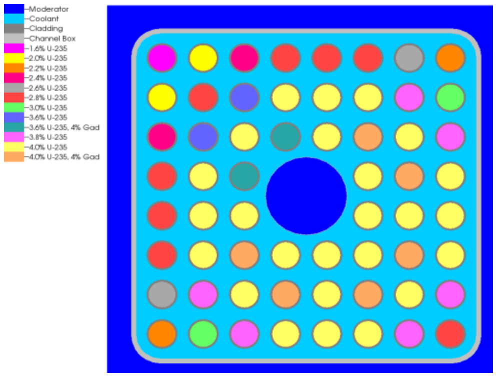
Assembly Void Map

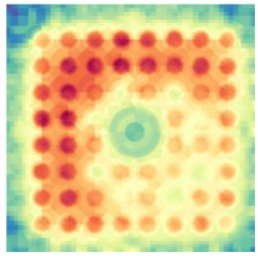
```
[STATE]
    void
      60.0 20.0
      40.0  0.0
```

$$\rho_{cool} = \left(1 - \frac{\alpha}{100\%}\right)\rho_{liquid} + \frac{\alpha}{100\%}\rho_{vapor}$$

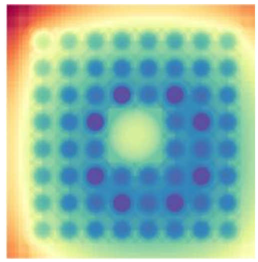


Demonstration of Large Water Rod (“GE-9 Like”)





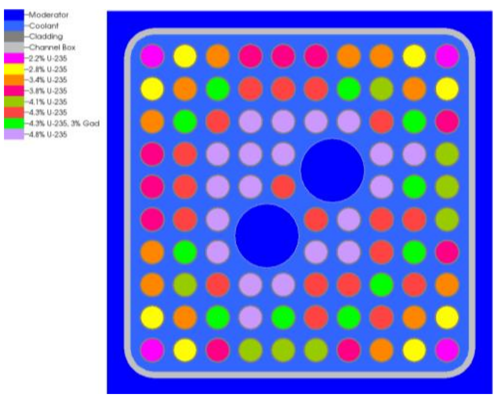
Group 1 Flux

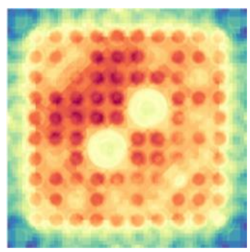


Group 47 Flux

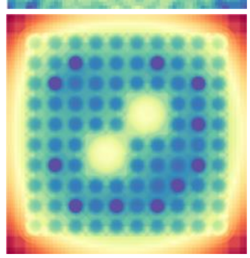
47-group library with TCP0
0.05 cm, 8 azimuthal, 2 polar angles
1e-6 convergence criteria (6 iters)
Run time: 47s (4 threads)

Demonstration of Large Water Rods (“GE-12 Like”)





Group 1 Flux

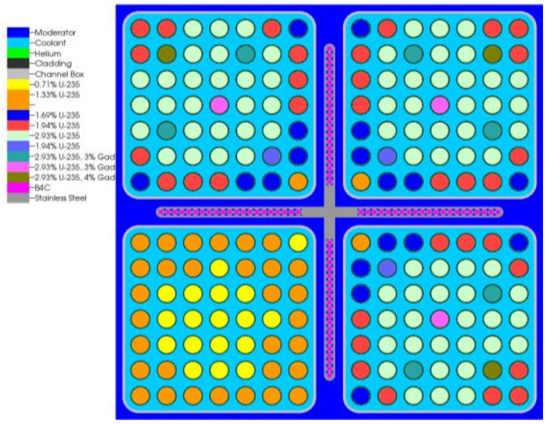


Group 47 Flux

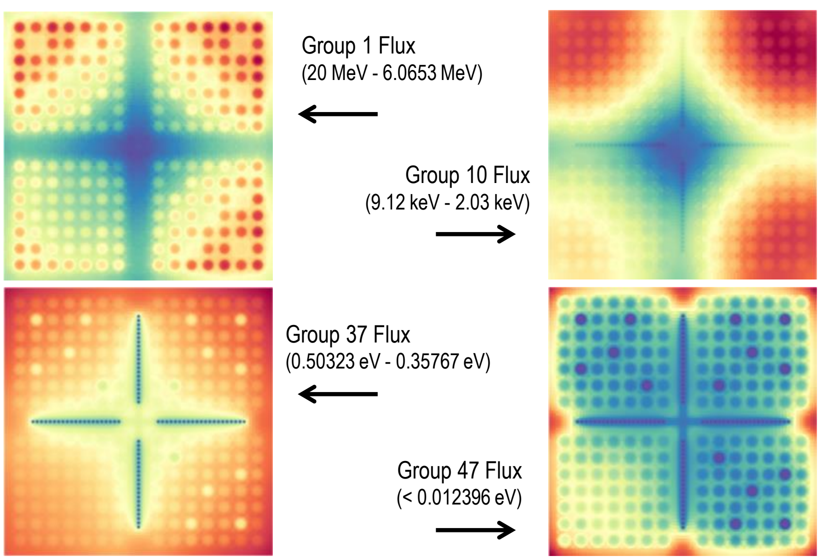
47-group library with TCP0
0.05 cm, 8 azimuthal, 2 polar angles
1e-6 convergence criteria (5 iters)
Run time: 62s (4 threads)

Demonstration of BWR Subregion (Multiple Assemblies)

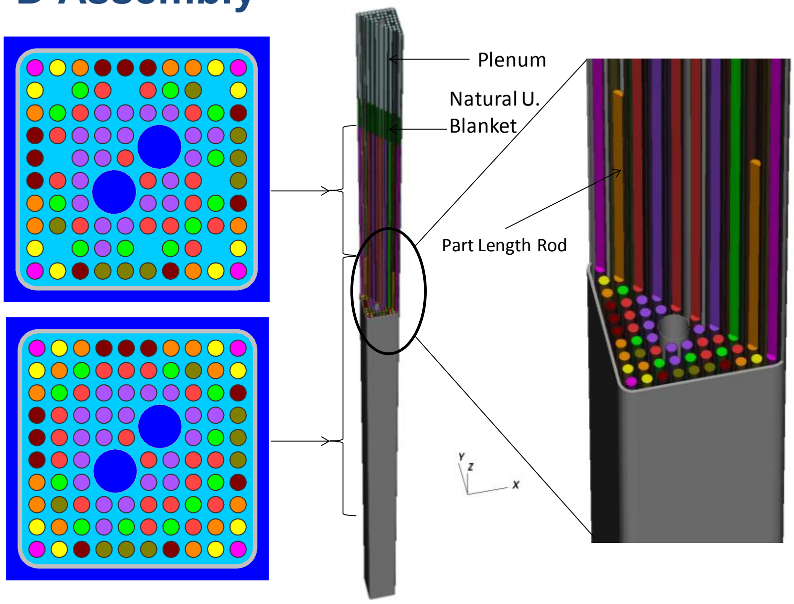
- BWR Control Cell
- Two assembly types
- Cold Zero Power Conditions
- 47-group library, P2 scattering
- 0.01 cm ray spacing, 16 azimuthal, 2 polar angles
- 1.0e-6 conv. criteria
- Converged in 9 iters
- Run time: 58 min (4 threads)



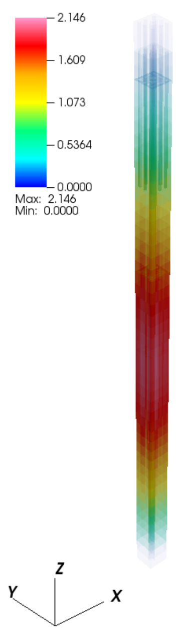
Demonstration of BWR Subregion



3-D Assembly



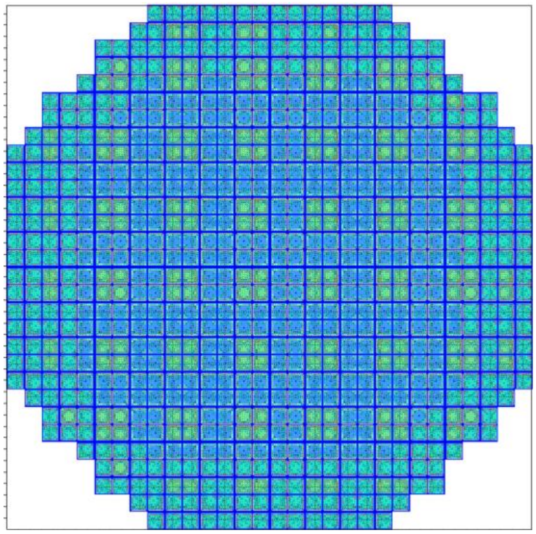
3-D Assembly

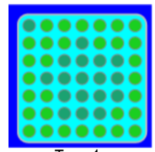


- Run on INL Fission cluster
  - 52 planes, 3" axial nodes in fuel, 4" axial nodes in plenum
  - 0.05 cm ray spacing, 8 azimuthal, 2 polar angles
  - 1e-6 convergence criteria
  - 47 group library with P2 scattering
  - Hot 0% void conditions
- Run time was 4 min 43 sec
  - Converged in 9 iterations
- Nozzles & axial reflectors not yet functional

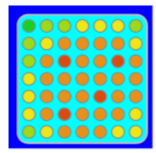
2-D Peach Bottom Unit 2 - BOC 1

No Control Rods
No Radial Reflector
Loading pattern is not exactly symmetric

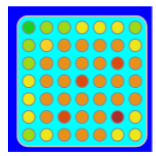




Type 1

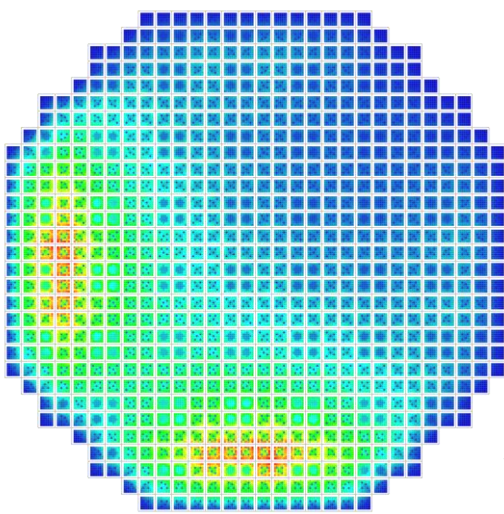


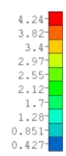
Type 2



Type 3

2-D Peach Bottom Unit 2 - BOC 1





764 processors
47-group, P2 Scattering
1e-6 conv. Criteria
Run time: 7 min 44 sec

Cold Zero Power (CZP)
With unsymmetric loading pattern

Relative Pin Power Distribution from VERAView

MPACT Milestone Conclusions

- Successfully met all primary objectives
  - Narrow and wide gaps
  - Channel box w/ rounded corners
  - GE OEM Control blade
  - Large water rods
- Did not meet secondary objectives
  - Thick-thin channel boxes, GE-11 designs, Atrium designs, GE-9 designs
- Met stretch goals: 3-D assembly and 2-D core

Table 8. Project Metrics

Metric	Value
Lines of Source Added	28,875
Lines of Test Added	44,895
Number of Unit Tests Added	24
Number of Regression Tests	25
Calendar Time	5 Months
Man Hours	>2364

BWR Future Work in MPACT

- Improve cross sections for voided cases
  - Fairly large errors found for voided cases
- Validation
  - Comparison to Monte Carlo continuous energy results
  - Independent methods
  - Waiting on new cross section library
- Investigate gadolinium depletion
- Multiphysics coupling to CTF

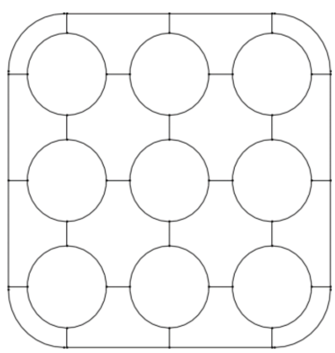
CTF Validation

- CTF Validation is an on-going effort:
  CTF Validation Report
  CASL-U-2014-0169-000 (Aug 2014)
  http://www.casl.gov/docs/CASL-U-2014-0169-000.pdf

- Additional BWR Validation added in 2015:
  CTF Void Drift Validation Study
  Milestone PHI.CTF.P11.04
  CASL-U-2015-0320-002 (Oct 2015)

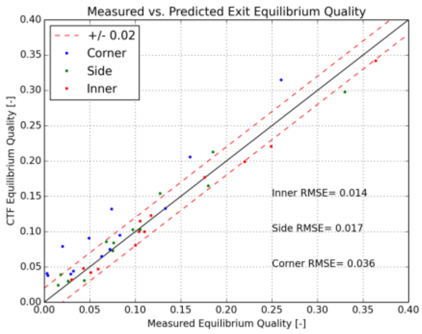
CTF BWR Validation

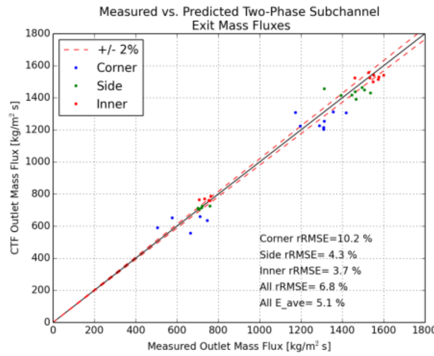
- GE 3x3 steam/water facility with BWR geometry and operating conditions
- Linear power density from 0 to 97 kW/m
- Inlet subcooling from 67 to 602 kJ/kg
- Inlet mass flux from 650 to 2,674 kg/s m^2
- Isokinetic sampling of channel mass flux, quality, and enthalpy



CTF BWR Validation

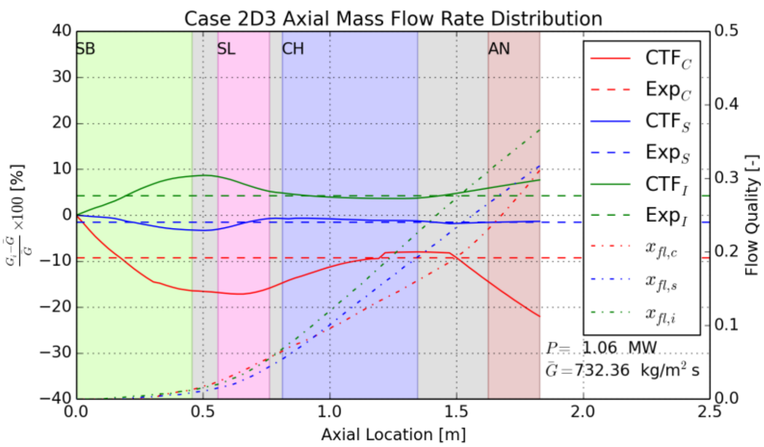
Measured vs. predicted exit quality and two-phase mass flux
Measured inner, side, and corner locations





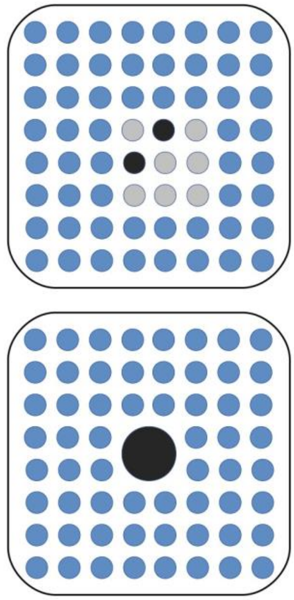
CTF BWR Validation

Axial normalized mass flux distribution for high power-to-flow ratio case



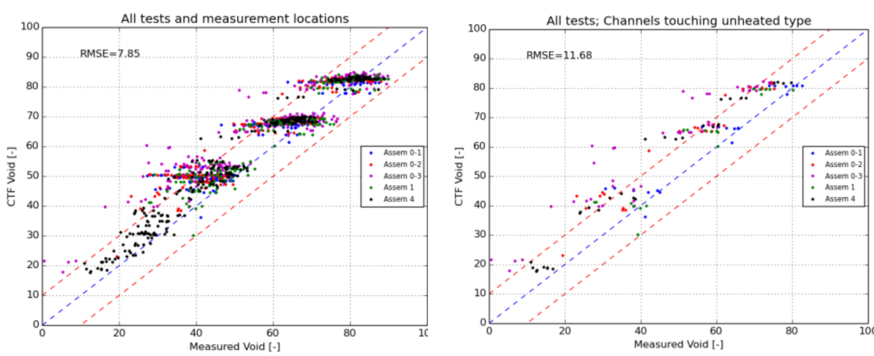
CTF BWR Validation

- BFBT 8x8 steam/water facility with BWR geometry and operating conditions
- Linear power density from 8 to 30 kW/m
- Inlet subcooling of about 50 kJ/kg
- Outlet quality from 5 to 30%
- Uniform and non-uniform power distributions
- Detailed outlet void measurements



CTF BWR Validation

Measured vs. predicted void for all assembly types and tests

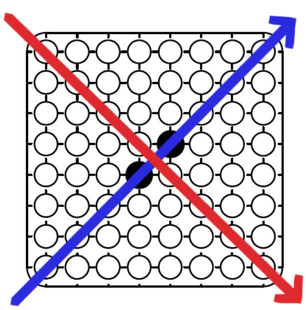


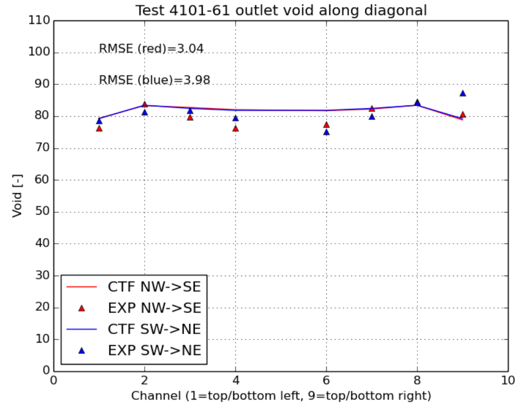
CTF BWR Validation

RMSE (%) of predicted void vs. measured void; sensitivity to void drift and droplet models

Channel Group	No Drops With Void Drift	With Drops With Void Drift	No Drops No Void Drift
Corner	7.61	8.43	11.47
Side	9.05	10.25	11.82
Inner	5.52	6.56	4.64
Unheated	11.68	13.67	11.56
All	7.85	9.06	8.95

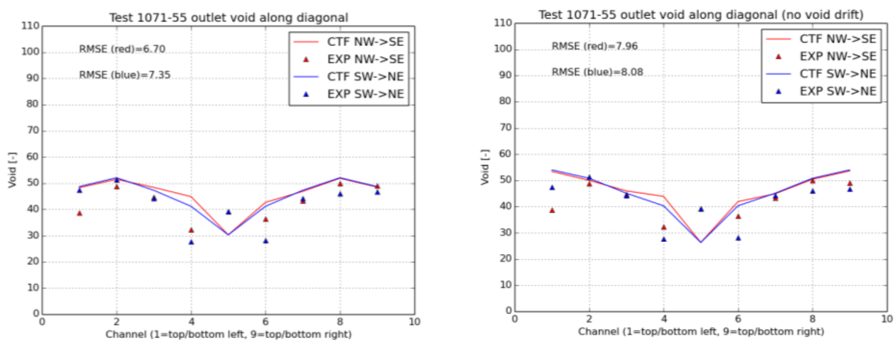
CTF BWR Validation





Void comparison for assembly with large water rod and high void

CTF BWR Validation



Void comparison for non-uniform power, two small guide tubes, and low void (with and without void drift model)

Planned CTF BWR Work

- Milestone L2:PHI.P12.01 (Jan 2016)
  - Develop BWR preprocessor to generate CTF input from VERAIn
  - Develop suite of single- and multiple-assembly CTF BWR models and run
  - Analyze results and make recommendations on improving code performance as necessary
- Milestone L2:PHI.P13.01 (April 2016)
  - Update validation and verification
  - Add RISØ tests to test matrix
  - Add BFBT critical power tests to test matrix
  - Add fuel rod validation/verification cases to test matrix
  - (V&V is an on-going process with CTF)

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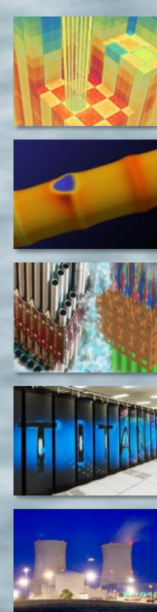
CASL Phase 2: Light Federal Touch

Alex Larzelere – United States Department of Energy

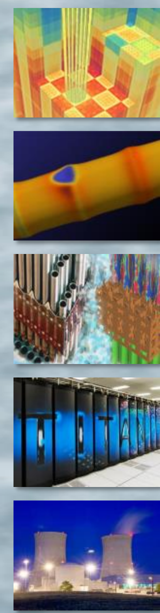
Separate attached pdf file of presentation



CASL The Consortium for Advanced Simulation of LWRs
A DOE Energy Innovation Hub

U.S. DEPARTMENT OF ENERGY

CASL Industry Council



Scott Thomas, Duke Energy
ORNL
November 5, 2015

The Consortium for Advanced Simulation of LWRs
A DOE Energy Innovation Hub

U.S. DEPARTMENT OF ENERGY

Industry Council

Assure that CASL solutions are "used and useful" by industry and that CASL provides effective leadership advancing the M&S state of the art

Objectives and Strategies

- Early, continuous, and frequent interface and engagement of end-users and technology providers
- Critical review of CASL plans and products
- Optimum deployment and applications of periodic VERA releases
- Identification of strategic collaborations between industry and CASL Focus Areas

Outcomes and Impact

- CASL benefits from advice on technical requirements, schedules, commercialization strategies, and computer requirements
- Industry Council can influence the CASL product to be compatible with expected applications and can better prepare internal technical and business processes

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Industry Council Membership

Owner/ Operators of Nuclear Plants	Fuel and/or SMR Vendors	Engineering Design, Service Providers, R&D	Independent Software Vendor	Computer Technology Companies	Ex-Officio
Dominion	AREVA	Battelle	ANSYS	Cray	BOD
Duke Energy	GNF	Bettis /NNPP	CD-adapco	IBM	DOE
EDF	B&W Power Generation	EPRI	Dassault Systemes	NVIDIA	
Exelon	NuScale	Rolls Royce	GSE Systems		
TVA	WEC	Studsvik Scandpower			

Industry Council Updates

- Industry Council leadership change
  – Scott Thomas will chair the Industry Council
  – Dennis Hussey will serve as Director

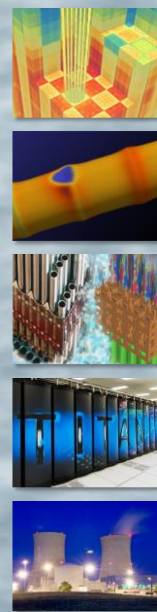
- New Members
  – Arizona Public Service
  – Southern Nuclear and Vattenfall

Phase 2 expectations are increased collaboration between IC and CASL team

Technology Deployment & Outreach (TDO) Progress Report

and

Update on VERA Working Group



Rose Montgomery
Industry Council Meeting
11/5/2015

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Outline

- Technology Deployment & Outreach (TDO) progress report
  - Goals
  - FY15 accomplishments
  - FY16 plans
- VERA Working Group plans

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A DOE Energy Innovation Hub

TDO Over-arching Goals

- TDO's priority is deployment and sustainability of the CASL technologies
  - Establish a means for long-term sustainability of the CASL technology
  - Ensure avenues for VERA deployment are open (EC/licensing)
  - Working with other CASL Focus Areas, manage external releases with respect to package contents, documentation, testing, expectations
  - Deploy VERA broadly; seek out and develop new users
  - Working with other CASL Focus Areas, support users while managing expectations
  - Engage with the nuclear community

TDO acts as a conduit for deployment of the CASL technology

FY15 Accomplishments

- Outreach
  - Development of training materials and delivery of training workshop at the ANFM Conference

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  - CASL.gov website update and planning for user portal

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FY15 Accomplishments

- Outreach
  - Development of training materials and delivery of training workshop at the ANFM Conference
  - CASL.gov website update and planning for user portal
- Test Stand deployment
  - Prioritization of potential test stand topics and hosts
  - Progress towards establishing an AREVA Test Stand and a University of Illinois Applied Research Institute Test Stand
  - Although not a Test Stand, Bechtel Marine Propulsion Corporation (BMPC) has installed VERA and is working with it

FY15 Accomplishments

- Releases
  - VERA3.3 release notes, readiness review, and release testing
  - VERA-EDU release plan, release notes, readiness review, and release testing
  - Created VERA documentation process and baselines and facilitated documentation improvements by developers
  - Began to establish user support functionality with internal notification process and preliminary response network

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  - VERA-EDU release plan, release notes, readiness review, and release testing
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  - Began to establish user support functionality with internal notification process and preliminary response network
- Post-CASL Entity
  - Preliminary market analysis for VERA

FY16 TDO Initiatives

- Develop VERA Deployment Strategy

FY16 TDO Initiatives

- Implement VERA Deployment Strategy
- Engage selected high value VERA Users

FY16 TDO Initiatives

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- Engage selected high value VERA Users
- Establish 2 or more external Test Stands

FY16 TDO Initiatives

- Implement VERA Deployment Strategy
- Engage selected high value VERA Users
- Establish 2 or more external Test Stands
- Improve and refine User services
  - such as VERA releases, User support, documentation, training resources, etc

FY16 TDO Initiatives

- Implement VERA Deployment Strategy
- Engage selected high value VERA Users
- Establish 2 or more external Test Stands
- Improve and refine User services
- Plan strategically for the future
  - Market analysis and VERA Working Group

FY16 TDO Initiatives

- Implement VERA Deployment Strategy
- Engage selected high value VERA Users
- Establish 2 or more external Test Stands
- Improve and refine User services
- Plan strategically for the future
- Further develop the EDU Program

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- Implement VERA Deployment Strategy
- Engage selected high value VERA Users
- Establish 2 or more external Test Stands
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- Plan strategically for the future
- Further develop the EDU Program

Critical to CASL Sustainability Effort

Engage selected high value VERA Users

- Nuclear community engagement is necessary, but must be balanced so as not to interfere with development
- TDO would like to continue / expand engagements with selected institutions / groups and provide demonstrations
  - Utility / vendors
  - PWROG / BWROG
  - INPO Driving to Zero
  - EPRI Fuel Reliability Program
- TDO is working with CASL staff to update communication vehicles
  - Website
  - TechNotes
  - Fact Sheets

Engage Users; Manage Expectations

FY16 Test Stands

- AREVA
- University of Illinois Applied Research Institute
  - We will likely provide a VERA training workshop here

FY16 Improve and refine User Services

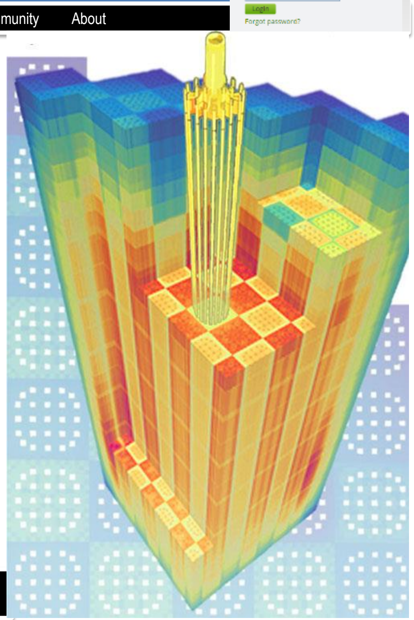
- Periodic VERA and VERA-EDU releases
- Continue/improve reasonable User support and/or set expectations
- VERA documentation continuous improvement
- Support VERA licensing

An agreed-upon balance between development and User support has to be created

Virtual Reactor.org
CASL VERA User Support Portal

Products and Services | Support | Community | About

- Registered Users
  - ✓ Download software and user manuals
- Access Tutorials
- Interface with the VERA user community
  - ✓ User simulations
  - ✓ Industry whitepapers
  - ✓ Post questions/issues
- Open and track user requests



New to VERA? Find out more about CASL and request a copy of VERA

The VRWG User Portal

- Primary point of contact for new and current users
- Access to documentation, tutorials, software updates for approved users
- The place to discuss VERA applications with the user forum
- Get VERA support
- Submit proposed VERA mods, example simulations, white papers

FY16 Plan Strategically for the Future

- Complete VERA market analysis
- Follow up on market analysis & post-CASL entity prioritization
  - Recommendations to SLT

FY16 Further Develop the EDU Program

- Complete VERA-EDU modules
- Host CASL Summer Institute

EDU Program aimed at academic use of VERA

FY16 VERA Working Group plans

- First meeting planned for late spring timeframe
- Invitees will include:
  - Current and past CASL members
  - Test Stand hosts
  - Industry Council membership
  - Science Council membership
  - Prospective VERA users (especially those that have already requested VERA)
  - DOE sponsors and stakeholders
- Likely to be held at ORNL

Idealized VWG Meeting Format

- 3 days
- Program Tracks
  - Organization / Administration
  - VERA R&D
  - VERA licensing, Verification & Validation
  - Education Program
  - Demonstrations
  - Hands-On training workshop

Initial meeting may be a subset

Idealized VWG Meeting Format

- Organization / Administration
  - Propose and ratify guidelines for VWG
  - Form governing body
  - Examine post-CASL entity options
  - Discuss options for computing support

First priority for initial meeting

Idealized VWG Meeting Format

- VERA R&D
  - Suggest PHI sponsor this track
  - Review progress to date
  - Discuss existing applications
  - Suggest applications for future development
    - Note that any suggestions would be for after CASL phase 2

Request IC/SC participation

Idealized VWG Meeting Format

- VERA Licensing, Verification & Validation
  - Suggest VMA sponsor this track
  - Review status and planning for V&V
  - Discuss need / want for licensing

Idealized VWG Meeting Format

- Education Program
  - Suggest EDU program sponsor this track
  - Review academic program plans and status
  - Augment long term plan as needed

Request EDU Council participate

Idealized VWG Meeting Format

- Demonstrations
  - Suggest TDO host
  - Open to all VERA Users
  - Present successes and issues

Idealized VWG Meeting Format

- Hands-On Training Workshop
  - Limited number of seats
  - 1 day (morning & afternoon) as presented at ANFM

Likely Content for First Meeting

✓ Organization / Administration
✓ Education Program
• Demonstrations
• Hands-On training workshop
× VERA R&D
× VERA licensing, Verification & Validation

Content will grow as VWG membership expands

Summary

- Significant progress in FY15 (in fact, ahead of TDO milestone schedule)
- FY16 is a critical year for TDO to establish sustainability
- Focus is on Users with implementation of new User Portal and the VERA Working group kickoff meeting

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Quick-Start Training Materials provide a cornerstone for getting users started with VERA (1 of 2)

- A general training program plan was developed that recommended establishing self-tutorials, training workshops, and web-based training materials.
- The ANFM conference was selected as CASL's initial training deployment target based on its past strong utility attendance
- With no prior materials to build from and only 18 weeks to deliver at ANFM, the timeframe was (and still is) considered to be extremely aggressive
- The VERA Progression Problem demonstration series (Godfrey, 2014) was selected as the basis of the Quick-Start tutorials.
  – Simple problems (entry level)
  – Few processors needed (2 to 16)
  – Aimed at familiarizing new users with the basic steps to run VERA

Quick-Start Training Materials provide a cornerstone for getting users started with VERA (2 of 2)

- Purchased a 64-core machine, LEZA, to provide classroom computing as a supplement to Titan.
- Developed background "methods" slides to familiarize attendees with the VERA methods and approach
  - Quick-start tutorials aren't meant to educate users on methods; that is included in the EDU program.
  - It is intended to get new users up and running with VERA quickly.
- A dry run with 13 students was held at ORNL to ensure the material was appropriate
- 15 students attended the Hands-on portion of the training at the ANFM conference (classroom was limited to 20 students, cost was $100 to attend)
- Feedback from the workshop was generally good.

TDO.VTRN.P10.01, TDO.CONF.P10.01 and 11.01; Eckleberry, Montgomery, Godfrey, Salko, Collins, Palmtag, Lewis, Ierulli, Baird, Turner, Mervin, Doster

BACK

Updated CASL website for Phase 2 and development of a new website for Users

- The Phase 1 CASL website was more towards informing visitors about the Innovation Hub itself - participants, organizational structure, research objectives
- In Phase 2, with increasing focus on deployment of CASL technology, CASL needed to shift the website to provide more emphasis on getting new users and sharing the technology
- Thus, the new website was mapped and has been developed

www.CASL.gov/NewSite

- Ready to go live

TDO.USPT.P11.03; Montgomery, Sieger, Lewis, Weltman, Cronholm

More on website work later today

BACK

SMR demonstrations illustrated VERA's ability to model iPWR

Objective: Evaluate VERA's ability to simulate an iPWR SMR.

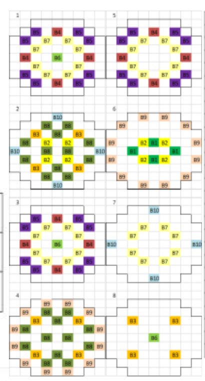
- ✓ Builds on work done in July 2014
- ✓ Incorporates control rod management similar to a typical BWR
- ✓ Utilizes coupled neutronics and subchannel thermal-hydraulics.

Illustration of the B&W mPower iPWR used as a basis for the model, courtesy of B&W.

1. Pressurizer
2. Once-Through Steam Generator
3. Feedwater Inlet / Steam Outlet
4. Reactor Coolant Pumps
5. Electro- Hydraulic CRDMs
6. Upper Internals
7. Reactor Core

Below left: Normalized assembly average and (peak pin power) observed during the cycle modeled. Center: ten bank control rod scheme analyzed with bank insertion depth.

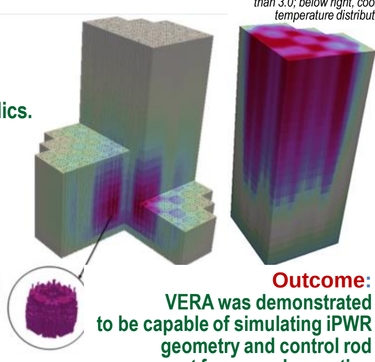
1.3469 (1.57281)	1.6767 (1.8178)	1.4706 (1.6877)	0.9617 (1.19726)	0.93924 (1.1604)
1.6767 (1.81773)	1.5816 (1.8150)	1.0615 (1.4632)	1.1343 (1.3078)	0.8786 (1.1442)
1.4705 (1.6877)	1.0615 (1.4632)	1.1375 (1.3520)	0.6860 (1.0282)	0.59224 (0.8879)
0.9615 (1.1972)	1.1342 (1.3077)	0.6859 (1.0282)	0.5050 (0.7672)	
0.9389 (1.1602)	0.8783 (1.1439)	0.5921 (0.8876)		



Move	EFPD	Bank	Steps
1	0	4	15
		5	15
		6	15
		7	15
2	150	2	20
		3	20
		8	0
		10	20
3	300	4	0
		5	0
		6	0
		7	0
4	450	3	0
		8	0
		9	0
5	600	4	30
		5	30
		7	50
6	750	1	60
		2	0
		9	0
7	900	7	50
		10	50
8	1050	3	50
		6	50
9	1200	ARO	228

Rods not shown are fully withdrawn

Maximum power peaking was observed at 150 effective full power days. Below left, core power distribution at 150 EFPD with inset showing locations with power peaking greater than 3.0; below right, coolant temperature distribution.



Outcome: VERA was demonstrated to be capable of simulating iPWR geometry and control rod management for normal operating conditions.

Although the core cycle design and control rod management were determined to be unacceptable with respect to power peaking, the work did exercise VERA functionality that is necessary to iPWR SMR simulation.

BACK

CASL.P10.01; Montgomery, Collins, Raine, Kenner

Test Stand Prioritization Document re-established selection criteria

- To evaluate the candidate applications proposed by each CASL industry partner, a characterization of each of the following attributes was provided to CASL for evaluation by the Senior Leadership Team (SLT).
  - Relative importance of the issue being investigated to the proposing host organization.
  - Capabilities contained in the VERA software and its ability to support the proposed application.
  - Amount of additional development required to support the proposed application.
  - CASL funding requirements (if any).
  - Ability of the Test Stand host organization to provide useful information and feedback to CASL to support further VERA development.
- Specific factors evaluated for proposed Test Stands:
  - relative importance of each proposed application to the host organization,
  - ability of VERA (in its current or near-term state of development) to support the application,
  - CASL return on investment – rigor of use,
  - CASL return on investment – support for VERA validation,
  - CASL return on investment – external staff funding.

TDO.TSTND.P10.01; Hess

Test Stand focus is on high-value potential users and rigorous use and feedback

BACK

Quality VERA releases in 2015

- Facilitated release planning
- Implemented a rigorous process for reviewing release readiness
- Added value for users in release notes
- Established baselines for user documentation and facilitated upgraded documentation in several areas

VEDU.P10.01, VREL. P10.01, P11.01, 11.02; VDOC.P10.01; Seiger

BACK

Preliminary Market Analysis for VERA

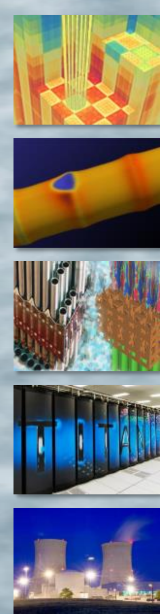
- Considers
  - Utility market
  - Use cases
  - Licensing models
  - Revenue scenarios & estimates of operational costs
- Concludes
  - User group model has several advantages
  - In early post-CASL years may operate on very little cash flow
  - Key is demonstrating value to utilities
- Recommends
  - Further investment in demonstrating applicability of VERA to industry, including consideration of NRC licensing

TDO.P10.01, TDO.WG.P10.01; CASL-U-2015-0144-000; Hussey

BACK

CASL Technology Deployment & Outreach Annual Workshop FY16

Oak Ridge National Laboratory
November 2 & 3



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Meeting Objectives

- The purpose for the meeting was to discuss TDO's FY16 milestones and:
  - Establish the product to be delivered
  - Determine what tasks are required to complete
  - Develop the schedule for the work
  - Assign the staff
  - Define the interfaces with other CASL FAs and external parties
  - Understand the obstacles and risks

You and your work are key to accomplishing TDO's mission!

Welcome! 11/2/2015

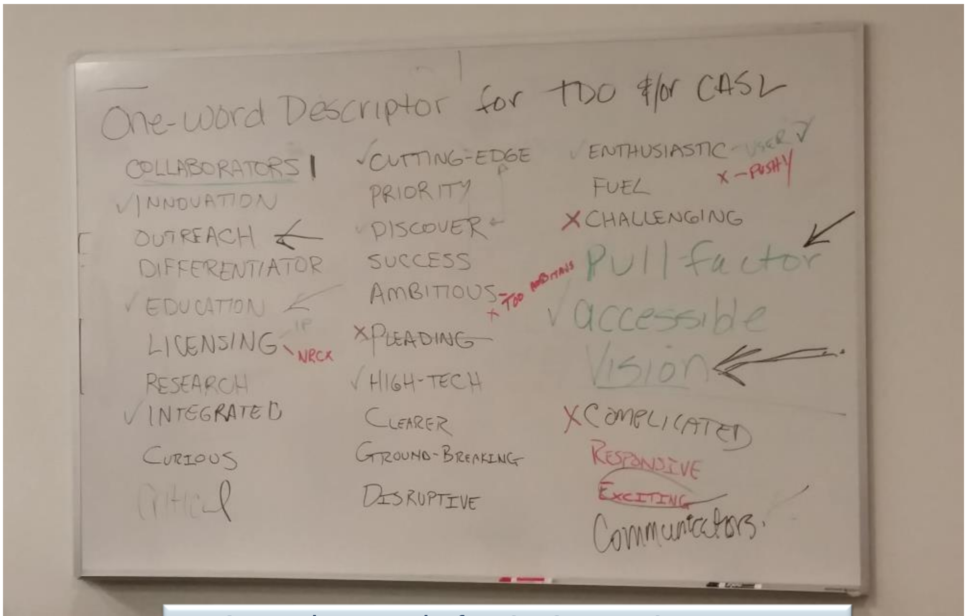
	Topic	Speaker
9:00 am	Welcome, safety moment, meeting objectives, introductions	Rose Montgomery
9:15 am	CASL's big picture and TDO's role	Jess Gehin, CASL Director
9:30 am	Industry perspective	Sumit Ray, Westinghouse
9:45 am	TDO Goals and FY15 accomplishments	Rose Montgomery
10:15 am	FY16 Big picture initiatives, project leads, and funding	Rose Montgomery
10:45 am	Status of VERA development effort	Kevin Clarno
11:30 am	Lunch on your own	
12:45 pm	Test Stand Project and milestones	Steve Hess
1:15 pm	AREVA Test Stand, topics, schedule	Steve / Chris Lewis
2:00 pm	CASL Education Program and Milestones	Mike Doster
	EDU module content to be developed, schedule, staff	
	CASL Institute planning	
	Student Summer Workshop planning	
3:00 pm	BREAK	
3:15 pm	Website updates / TechNotes	Rose Montgomery / April Lewis
3:30 pm	Quick-start training refinements + additional tutorials; Training Dates and places	Rose Montgomery
4:30 pm	Wrap up for the day – action items, general discussion, logistics	Steve Hess
4:45 pm	adjourn	

Tomorrow's Agenda 11/3/2015

	Topic	Speaker
8:30 am	Welcome, diversity moment, meeting objectives	Steve Hess
8:45 am	Post-CASL Entity project and milestones	Bob Oelrich
9:00 am	Market analysis status and FY16 work	Sarah Edge
9:30 am	VERA Brand Values and FY16 work	Bob Oelrich
9:45 am	Discussion: Post-CASL entity - what is the path forward	Bob Oelrich
10:00 am	BREAK	
10:15 am	Releases & User Support Projects and milestones	Matt Sieger
10:30 am	VERA distribution via RSICC & Scheduled VERA RSICC releases (standard and edu)	Mark Baird / Matt
10:45 am	VERA tarball creation for distribution (releases); daily tarballs; investigate binary distribution versions	Brenden Mervin
11:00 am	Continuously improve documentation	Matt
11:15 pm	User Support / Strategy	Matt / Brenden
11:30 am	For discussion: expanded release testing needs; repo structure	Matt
12:00 pm	Lunch on your own	
1:00 pm	VERA Working Group	Rose
2:00 pm	Plans for Systems Level simulations with VERA PIRT status & schedule	Vince Mousseau
2:30 pm	WBN-2 simulation status and schedule Reactivity control simulations	Rose / Kara Godsey
3:00 pm	BREAK	
3:15 pm	Export control considerations for VERA and VERA.edu	Matt Sieger/ Sam Howard / Jeff Banta
3:30 pm	Licensing approach for VERA, VERA.edu	Kathleen McDonald / Jeff Cornett
4:00 pm	For discussion: Information about requests for VERA and how they are being handled right now	Matt
4:30 pm	Wrap up for the day – action items, general discussion	Rose
5:30 pm	adjourn	

CASL SLT Priorities for TDO in FY16

- **Develop approaches and concepts for post-CASL sustainability**
  - Input to SLT milestone to DOE and Board of Directors
- **Increase visibility of CASL research and development**
  - TDO role in this is through the website, releases, Test Stands, TechNotes, and training
- **Mature releases and support processes within CASL**
  - Work with FAs developing the capability to determine roles for releases and support
- **Successful execution of the Education Program CASL Summer institute**



Some keywords for CASL, TDO & VERA

CASL Industry Council
Test Stand Plans and Milestones

Stephen Hess (EPRI – TDO Test Stand Lead)

5 November 2015

Test Stand Strategic Vision

The strategic vision for CASL in Phase 2 and beyond sees its M&S technology evolving into the nuclear enterprise community model for nuclear reactor and power plant M&S technology. Early adoption and technology transfer to the nuclear energy community throughout Phase 1 and 2 in the form of Test Stands, the post-CASL entity, M&S working group, and broad release of VERA will demonstrate industry acceptance, integration and adoption. Broad engagement of the nuclear community allows CASL to build interest, trust, confidence, and acceptance of M&S methods and tools across the nuclear engineering

Test Stand Objectives

- Serve as a primary mechanism for early deployment of CASL-developed technology to key stakeholders
- Provide direct stakeholder feedback on VERA usability and capability
- Permit additional demonstrations of CASL developed capabilities on applications that are not directly addressed as part of the CASL development effort

Status of Test Stands

- CASL Test Stands were instrumental to CASL Phase 1 success
  - Extended VERA user base
  - Provided opportunity for (relatively) unbiased feedback
  - VERA used in diverse applications
  - Offered potential for additional validation
  - Developed Phase 2 user support strategy
- Phase 1: Test Stands piloted by CASL Founding Partners
- Phase 2: Shift of focus to "External" hosts
  - CASL Partners

Test Stands will continue throughout Phase 2

Experience from Test Stands

- Execution of three Test Stands during Phase 1
  - Westinghouse: Zero Power Physics Test Simulations for the AP1000 (Technical details in CASL-U-2014-012-001)
  - EPRI: Evaluation of Peregrine as a State-of-the-Art Fuel Performance Code (Technical details in CASL-U-2014-121-000-a)
  - TVA: Investigation of PWR Lower Plenum Flow Anomaly (work currently in progress in final stages of completion)
- User feedback from Test Stand experience documented in 2014 AMA Milestone reports
  - Initial user experience in CASL-U-2014-0036-000 (March 2014)

7-000

Westinghouse Test Stand recognized with receipt of IDC HPC Innovation Excellence award

Test Stand Selection Process

- Phase 1: process developed to select Test Stand topics (CASL-U-2014-0036-000)
- Reviewed Summer 2015 to update process and provide recommendations for Phase 2 (CASL-S-2015-0259-000)
  - Recommended continued use of basic process and criteria
    - Host Proposal → CASL Review / Prioritization → Discussions / Selection → Project Initiation
  - To maximize successful transfer to broad nuclear energy community with focus on industry use – proposed objective to conduct 2 Test Stand deployments per year during Phase 2
  - Conducted initial review of proposed AREVA and UIUC Test Stand proposals for deployment in 2016
  - Proposed plan for 2017 – 2019 Test Stands by host role within nuclear power industry

Test Stand Selection Criteria

- Relative importance of the issue being investigated to the proposing host organization
- Capabilities contained in the VERA software and its ability to support the proposed Test Stand application
- Readiness of VERA capabilities and the amount of additional development that that would be required to support the proposed application within the proposed timeframe
- CASL funding requirements needed to support the VERA deployment and proposed Test Stand application
- Ability of the Test Stand host organization to

Phase 2 Test Stand Schedule

- Fiscal Year 2016: NPP Operator / Supplier (AREVA) | Educational Institution (UIUC)
  - AREVA: Application selected / contract in process / project kickoff and VERA training scheduled week of 14 December
  - UIUC: Initial assessment complete / contract and SOW in process
- Fiscal Year 2017: NPP Operator / Supplier (Utility) | Regulatory Authority (US NRC)
- Fiscal Year 2018: NPP Operator / Supplier (GNF – BWR Application) | Educational

…lier

"Highest Value" Application

Look to extend outreach and leverage Industry Council and Working Group members to identify worthwhile Test Stand hosts / applications

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AREVA Test Stand Problem

CASL Project

November 2, 2015

Background

- AREVA contracted with CASL (AREVA Test Stand Phase 1) to:
  - Install VERA code on AREVA platform
    - Acquire from RSICC
    - Compile on AREVA computing platform
    - Run validation suite
  - Set up and execute VERA 2D and 3D neutronics models on an AREVA fuel design
    - Selected TMI Cycle 1 design
  - Deliver a non-proprietary written report detailing results and findings
  - Develop a proposal to CASL regarding potential test stand problems for AREVA Test Stand Phase 2

AREVA Test Stand Phase 1 Status

- VERA Installed on AREVA system
  - No major issues encountered during install and validation testing
  - Set up TMI Cycle 1 Core Depletion
    - Identified some code issues
    - Working with CASL Technical team to resolve
    - Have started depletions for Watts Bar 1 (going for week now)
  - Proposal delivered to CASL regarding potential test stand problems
    - Discussed next

Proposed Test Stand Problems

- Thermal-Hydraulics (CHF/DNB)
  - Evaluate Past CHF Test Data with VERA
    - Evaluate axial and azimuthal behavior in 2θ of past CHF testing
    - Data available for several older grid designs
    - Develop CFD models of tests and compare to past AREVA results
    - Demonstrates performance of (or identify areas for further improvement in) TH modules in VERA
- Thermal-Mechanical (Cladding Performance)
  - Evaluate fuel rod performance with VERA
    - Data available for a MOX rod or 10 w/o Gadolinia rod
    - Develop BISON models and compare results to past AREVA results
    - Demonstrates performance of (or identify areas for further improvement in) CASL-BISON in VERA

Proposed Test Stand Problems

- Core Simulator (Neutronic Performance)
  - Evaluate core simulator performance with VERA
    - Data available for a Catawba (C1) MOX rod
    - Develop Catawba cycle depletions and deplete rod to EOL
    - Compare rod burnup and isotopics to measured results
    - Demonstrates performance of (or identify areas for further improvement in) VERA core simulator\
  - Evaluate VERA coupled-code capability to analyze an RIA event
    - Develop a VERA-CS model for an existing AREVA plant
    - Benchmark BOC HZP parameters
    - Model a BOC HZP RIA event
    - Compare results to AREVA's ARCADIA coupled-code system RIA methodology

Proposed Test Stand Problems

- Clad Corrosion/Water Chemistry (CRUD)
  - Evaluate Past CRUD Events in operating plants (Deposition and CIPS)
    - Data available for several events
    - Develop a VERA-CS model along with CFD and MAMBA models to calculate local crud thicknesses and potential B^{10} uptake
    - Demonstrates performance of (or identify areas for further improvement in) VERA in a coupled system calculation

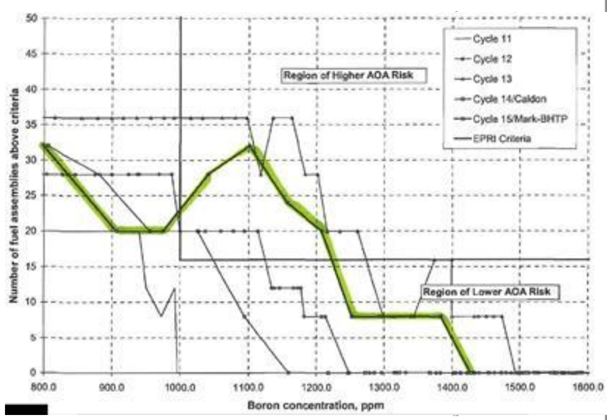
>> Problem Chosen by CASL Team for AREVA Test Stand Phase 2

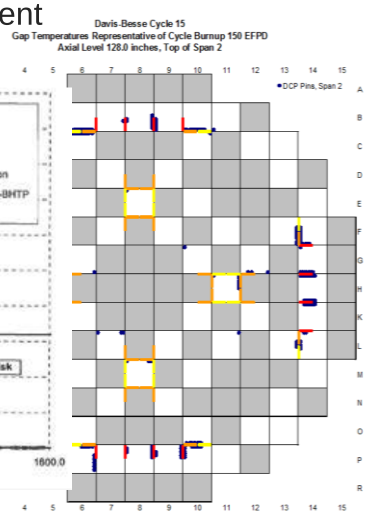
AREVA Test Stand Phase 2

- Davis Besse Cycle 15 CRUD Event

AREVA Test Stand Phase 2

- Davis Besse Cycle 15 CRUD Event





AREVA Test Stand Phase 2

- Modeling Davis Besse Cycle 15 CRUD Event
  - Deplete Davis Besse Cycles 1-15 in VERA
    - Provides another verification of VERA's ability to model:
      - Different core/fuel configurations (B&W 177 assembly core w/15x15 fuel)
      - Different burnable poisons (discrete BP rods and gadolinia)
      - Handle core shuffles
  - Restart Cycle 15 calculation with CFD/MAMBA modules
    - Evaluate crud deposition (thicknesses and locations) and compare to measured
    - Evaluate CIPS impacts on measured/calculated core axial offset
  - Document results and report to CASL

CASL: Consortium for Advanced Simulation of Light Water Reactors

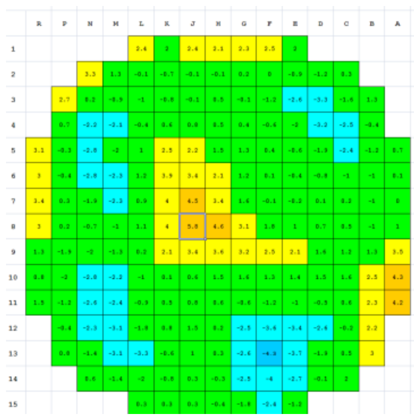
TVA Test Stand Status Report:

Simulation of Typical Westinghouse 4-loop Lower Plenum Flow Using Hydra-TH

November 2015

Background on Lower Plenum Flow Anomaly (LPFA)

- Many plants (10+) have reported observations associated with LPFA
- Power, flow and temperature measurements deviate from predictions
  - Pattern repeated over many operating cycles
- Postulated root causes
  - Flow vortices within the reactor vessel during operation
    - Standing vortices or periodic
  - Susceptible design and/or as-built geometry, including asymmetry in lower internals and loop inlet/outlet placement
  - Loop flow differentials, including geometric differences in loop geometry
- Possible influencing parameters
  - Reactor Coolant Pump impeller replacement
  - Pump startup sequence

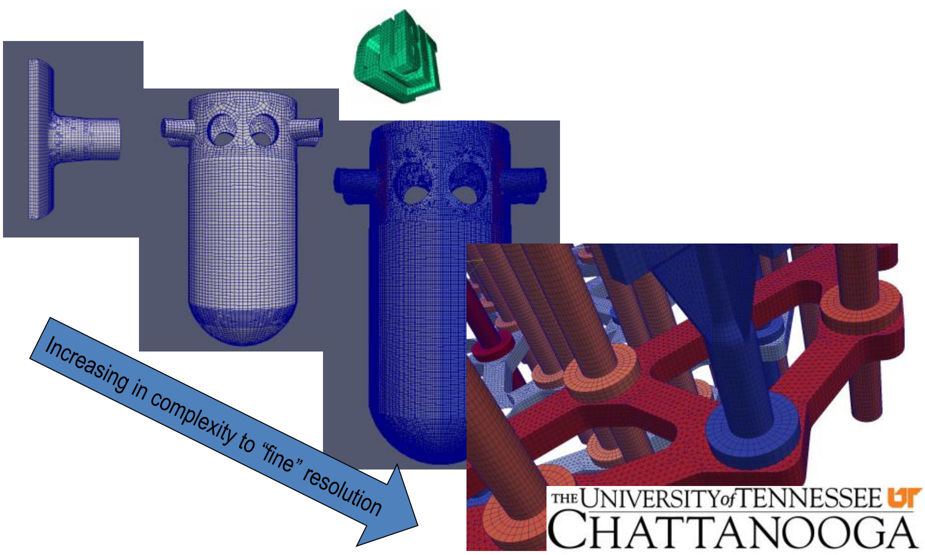


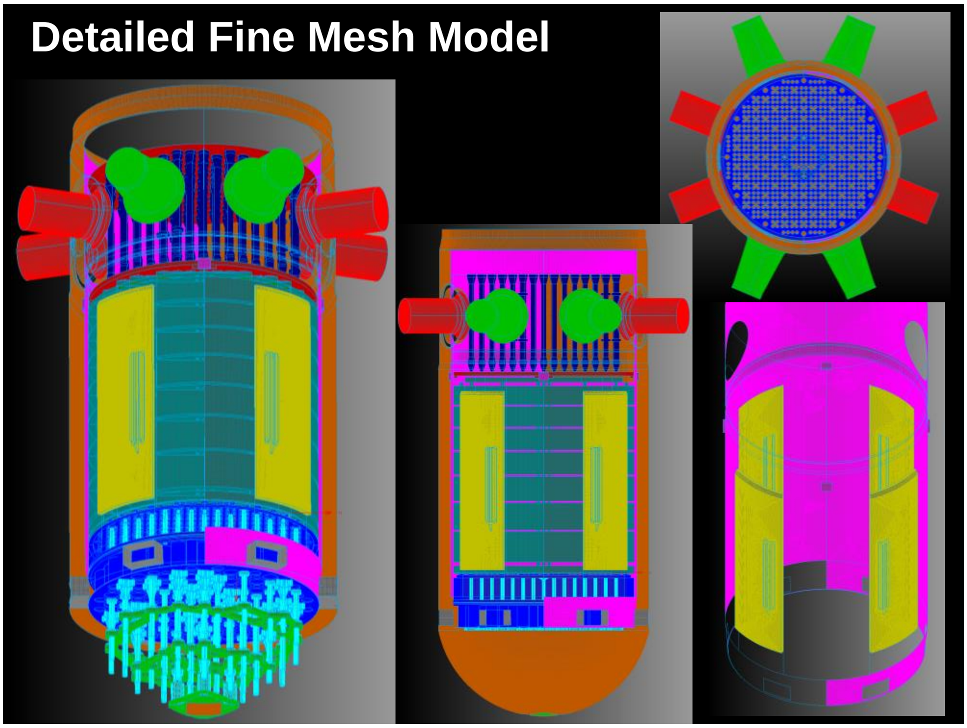
Byron Station, cycle 18

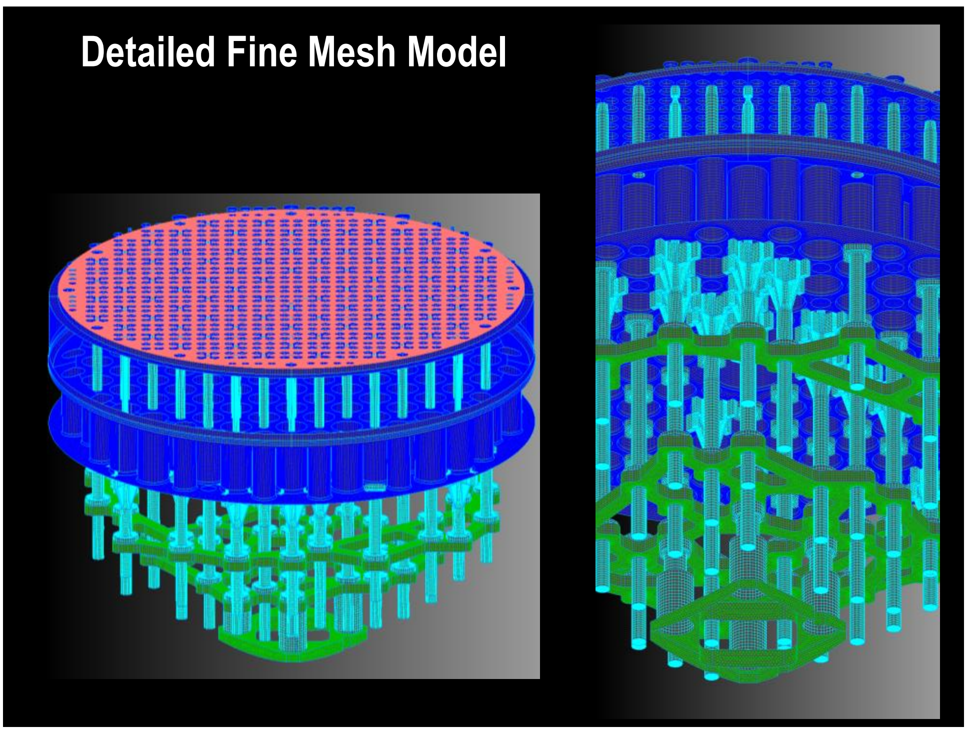
Mesh development progression

- *Several representations of the geometry were constructed and used in simulations with Hydra-TH:*
  – Just an inlet nozzle (4K cells)
  – Inlets and downcomer only
    - Coarse mesh (?? K cells)
    - Moderate mesh (479K cells)
  – Inlet, downcomer, and lower plenum without lower internals package
    - Coarse hex mesh (525K cells)
    - Coarse tet mesh (328K cells)
  – Inlet, downcomer, and lower plenum with lower internals package, but without the core
    - Moderate mesh (?? K cells)
    - Fine mesh (455M cells)
  – Inlet, downcomer, lower plenum with lower internals, porous media core region with outlet (partial upper plenum)
    - Fine mesh (448M cells)
  – Porous media core (2.92M cells)

Progression in model development




Detailed Fine Mesh Model


Detailed Fine Mesh Model

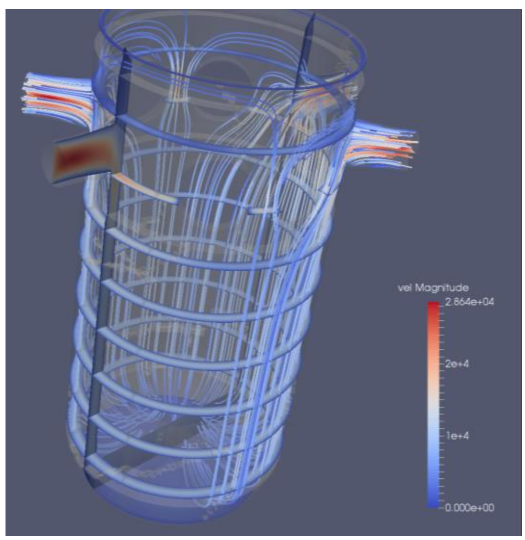
Initial Simulations

- Working with the smaller models and progressing to the more detailed representations allowed TVA to learn how to use Hydra-TH
- Mesh Density studies
- Convergence criteria studies
- Solution methods & time integration parameter studies (fixed CFL/fixed time step and semi-implicit/fully-implicit)
- Parameterization studies (velocity, pressure BCs)
- Turbulence model selection
  - Only the RNG k-ε model consistently arrived at a converged solution

Note that these studies utilize a Reynold's Averaged Navier-Stokes (RANS) approach. It isn't clear that this approach can fully predict the LPFA phenomena, but was selected as a place to start with Hydra-TH.

Example Parameter Study on Inlet Velocity

- Pump Startup Sequence
  - Purpose was to generate an unsteady flow condition and check method of input of inlet BC
  - One pump running at time = 0. Remaining pumps start at 300, 600, 900 seconds
  - Steady state results after 4th pump starts similar to convergence study case with all 4 pumps

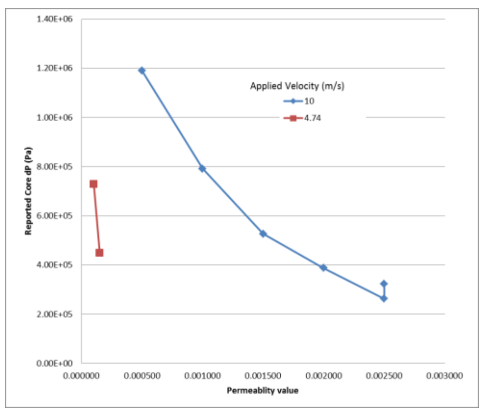


Recent Simulations – fine mesh with lower internals geometry but without core region

- Model has not been run successfully
  - Initial attempts were unsuccessful due to a need to recompile Hydra-TH on Titan following a system upgrade
    - Model ran but results were reported as all zeros (petsc issue)
    - This wasted a large portion of our allocation
  - Time and allocation constraints led us to move on to modeling the porous media core region and then the fine mesh reactor model with porous media core representation

Recent Simulations – porous media

- Calibration of the porous media region
  - Porosity and permeability are specified;
  - Porosity was assigned based on vendor-reported loss coefficients for each grid/rod span;
  - Permeability was planned to be used to achieve the vendor-reported pressure drop associated with the assembly / span given a specific inlet flow
  - Simulations have not successfully tuned the porous media model to match the vendor-reported pressure drop
  - More cases would need to be run.



Fine mesh with lower internals geometry and with porous media core representation

- Inlet flow BC taken from Watts Bar unit 1 operating history, ranging from 97.5% flow at one inlet to 101.0% flow at another
- Isothermal conditions (no fuel rod heat generation or conjugate heat transfer)
- Model has not been sucessfully run as a complete system
- Ran out of time / allocation
- Porous media tuning incomplete

Computing Resources used

- Size and complexity of model requires significant computing resources
  - 1200 nodes on Titan, anticipated 36 hours of run time to steady flow for the full model = 700,000 core-hours per simulation
  - Of the 1200 nodes, only 50% of cores were used for actual calculations. The remaining cores were idle to provide necessary memory to the active cores (Titan has 32 GB RAM available per node)
  - Long queue times on Titan
- Limited TVA allocation on Titan
  - For the Test Stand, TVA requested and received an industry allocation outside of CASL
  - Given our unfamiliarity with Hydra-TH and prior to having mesh, we guessed at what allocation was needed (badly) as 1 million core-hours
  - Available core hours allowed for only 1 or 2 runs with the full model
- Exploring possibilities for continuing

TVA Test Stand - Successes

- Total cases run >100
- Good working knowledge of setting up models in Hydra-TH
- Simplified reactor geometry with coarse mesh were successful and reliably produced converged solutions
  - Demonstrated use of Hydra-TH for transient flow simulation in a nuclear reactor
  - Steady state results following staggered reactor coolant pump startup sequence essentially identical to simultaneous startup of all four pumps.
- Demonstrated process for utilities or other external partners to obtain a high performance computing resources to run simulations of interest with VERA.
  - Utilities generally do not possess the computing resources required to run large scale simulations with VERA
  - Partnership with OLCF provides utilities with an avenue to access the required HPC resources
  - Allocation process was straightforward but should be requested well in advance of need date

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Lessons Learned – Hydra-TH

- Steep learning curve with Hydra-TH
  - Hydra-TH User Manual is designed to provide “sufficient information for an experienced analyst to use Hydra-TH in an effective way”
    - Primary TVA engineer was a CFD novice
  - There are a lot of “knobs” available to tune the time integration and solution parameters
    - We didn’t find any guidance on which combination of parameters are required to successfully converge a given problem and had to rely on experimentation and help from the Hydra-TH team when desperate
    - Settings that worked for one problem didn’t work for a similar problem
    - Much allocation and engineering time was devoted to figuring out what combination worked for each mesh and BC
- Hydra-TH still in development during test stand
  - Porous media option used to model fuel region was not available at start of test stand
  - Turbulence models were still in development at start of test stand
  - Frequent recompile & builds due to changing Hydra code and Titan upgrades hindered progress

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Lessons Learned – Visualization

- Visualization of results for the really large models required significant computing resources
  - ParaView was available for visualization on Rhea
    - Software only available while on-site at ORNL
    - The ParaView team was extremely responsive to our requests
    - Very slow response using Rhea in client-server mode made it almost impossible to visualize results
      - Recent development using hardware rendering with GPUs has been implemented in the last few weeks (on Titan) and has greatly increased speed

Lessons Learned – Organizational Issues

- Prioritization of Test Stand within TVA
  - Needs of TVA's operating fleet took priority over Test Stand work, limiting manpower availability
    - Baseline work and emergent plant needs
  - Primary TVA Test Stand engineer was assigned to another project for a significant portion of the test stand period, limiting his availability and causing delays
- Collaboration between TVA and CASL was not as strong as it should have been
  - User support was not always readily available from the Hydra-TH development team at LANL
  - Support at both LANL and ORNL became more available during the latter portions of the test stand period
  - LANL staff assisted in tuning the input decks for successful execution at several stages

Remaining Work

- Resolve porous media issues
- Completion of full reactor model run in Hydra-TH
  - Explore possibilities for completing the run under new or existing Titan allocations, on other national lab resources, or identify other options
- Explore potential to import mesh to STAR-CCM+
  - Going forward, CASL will be using STAR-CCM+ for CFD modeling in place of Hydra-TH
  - Potential for comparison between Hydra-TH and STAR-CCM+
  - Also potential for sharing mesh with others (EdF, Westinghouse) was proposed but hasn't yet been fully discussed
- Complete Test Stand Documentation
  - CASL Report
  - OLCF project close-out report

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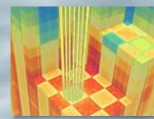
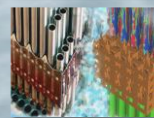
VERA Licensing & Release Process

Matt Sieger
Mark Baird





Accomplishments & Challenges

- Recent Accomplishments
  - VERA 3.2 (September 2014)
  - VERA 3.3 (April 2015)
  - VERA-EDU 3.3 (September 2015)
  - The release process is steadily improving & becoming more routine
  - Partner agreements for licensing
  - Test & Evaluation license for individual users completed
- Challenges
  - Active development driving rapid change
    - Necessitates collaborative release planning
  - Licensing/Export Control
  - Support & deployment communications

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Current Activities

- We are preparing for the VERA & VERA-EDU 3.4 release due Nov 30
  - Includes capabilities up to the Core Simulator Progression Problem 10 (multi-cycle with depletion)
  - Standalone BISON
- Deploying RSICC portal for VERA requests that supports our deployment process & licensing
  - Will be prepared to intercept this release
- Plan is to support quarterly releases with incremental capability updates
  - Subject to development progress
  - We are improving our test capability to enable rapid patch deployment, this may take pressure off of full release cadence

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Software License Agreements

A Must for Deployment of CASL-Developed M&S Technology

- **What is CASL prepared to license?**
  - VERA in its entirety (including all core simulator and advanced components)
  - Partner agreements prevent CASL from distributing individual components – those can be obtained from the owners
- **What types of license agreements will CASL execute?**
  - ✓ *Government Use*: use must fall within scope of an existing government project
  - ✓ *Test & Evaluation*: use for a limited period
  - *Non-Commercial*: restricted to R&D/educational/nonprofit purposes (in progress)
  - *Commercial*: use as part of a profit-based business plan (in progress)
  - Both individual and site licenses
- **Principles**
  - Ability to license VERA with a single agreement
  - Consistent terms and conditions for each VERA component
  - Non-commercial and commercial license fees nonzero but minimal

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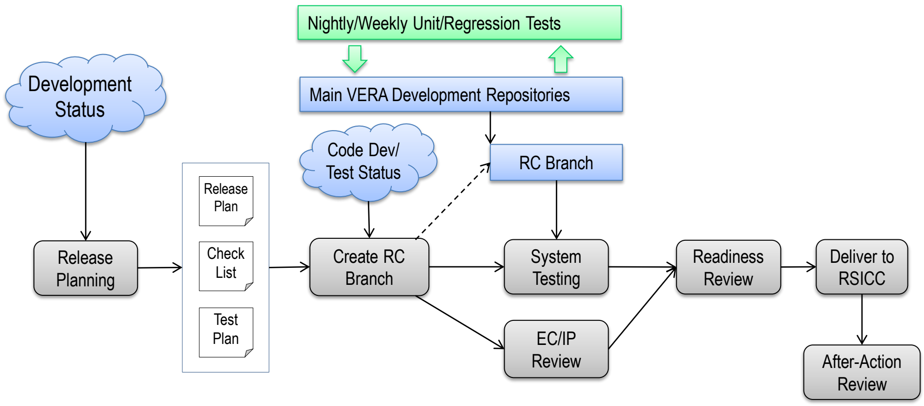
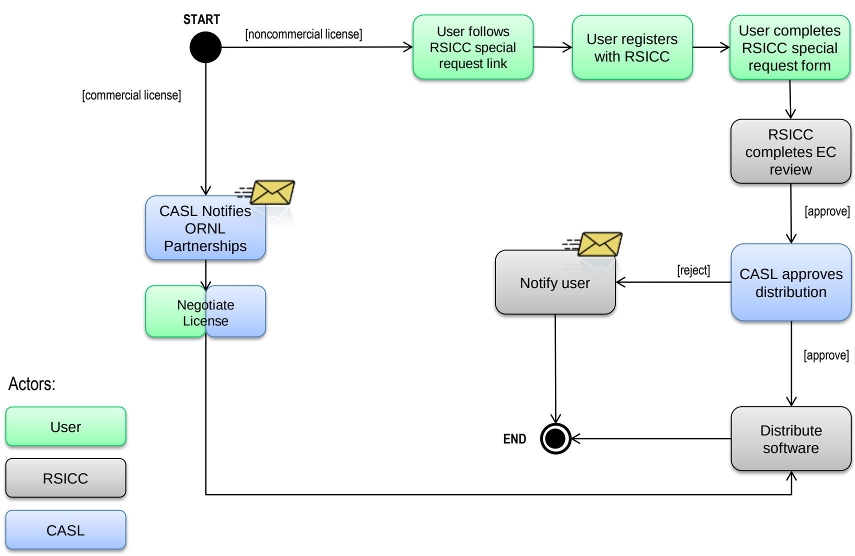
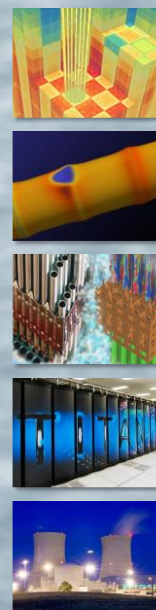
VERA Release Process



New User Process (V3.3)



VERA Request Process through RSICC



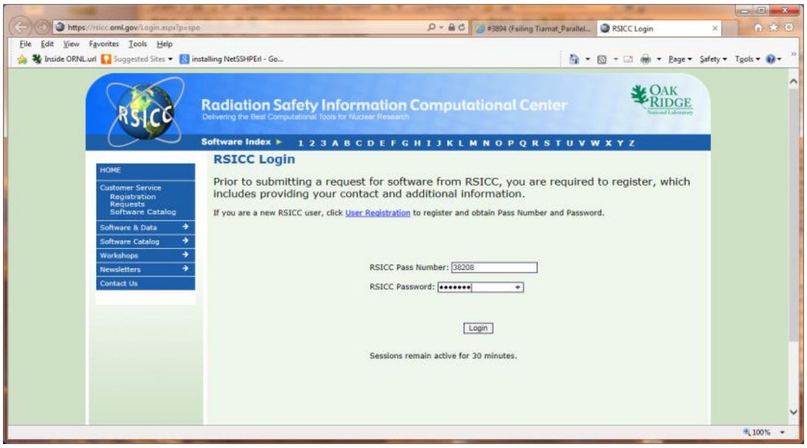
The Consortium for Advanced Simulation of LWRs
A DOE Energy Innovation Hub

U.S. DEPARTMENT OF ENERGY

Distribution Control

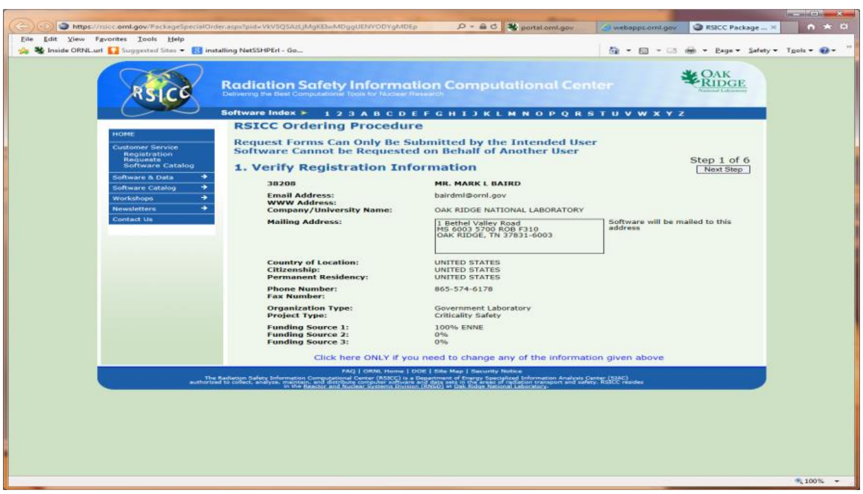
- VERA can be requested using a special link.
  - Private distribution only, will not be visible to the “World”
  - CASL will approve individual requests.
- Users can click on this link and request the correct version of VERA:
- https://rsicc.ornl.gov/PackageSpecialOrder.aspx?pid=VkVSQSAzLjMgKElwMDggUENYODYgMDEp

RSICC Login Page



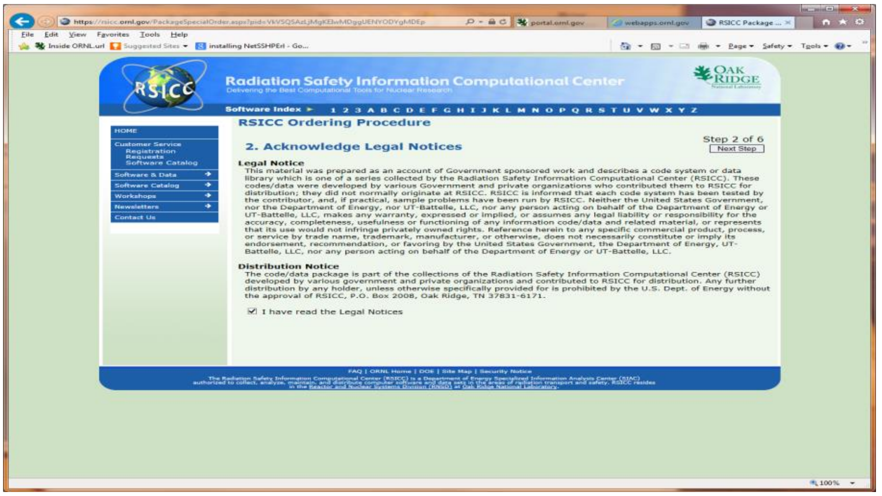
- After clicking on link users are prompted for login credentials.

User Information

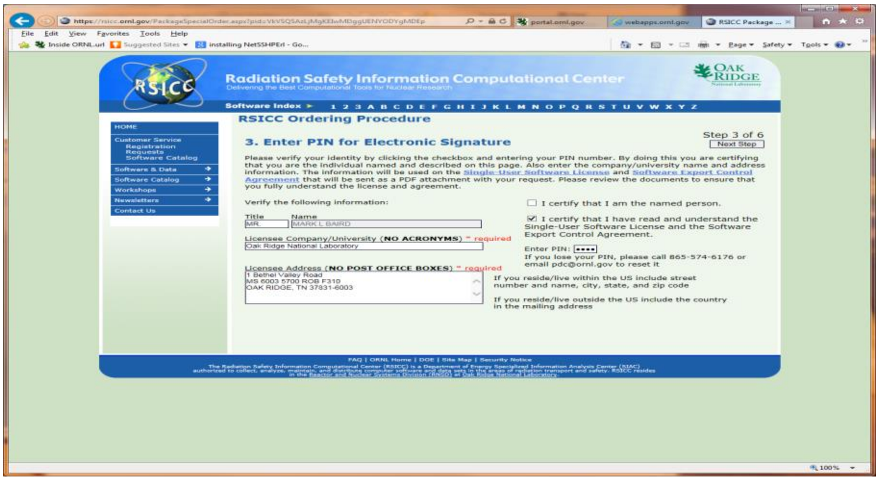


- Users are required to verify Institution and funding information.

Legal Notices

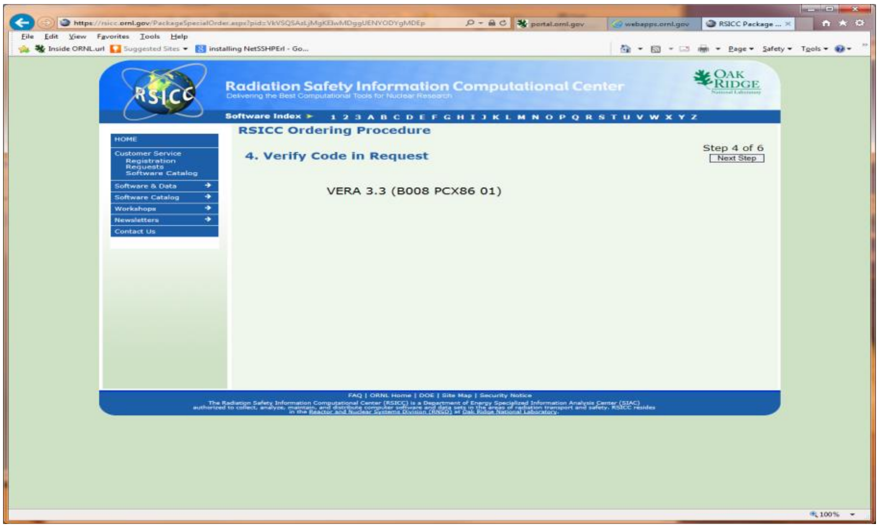


E-signature



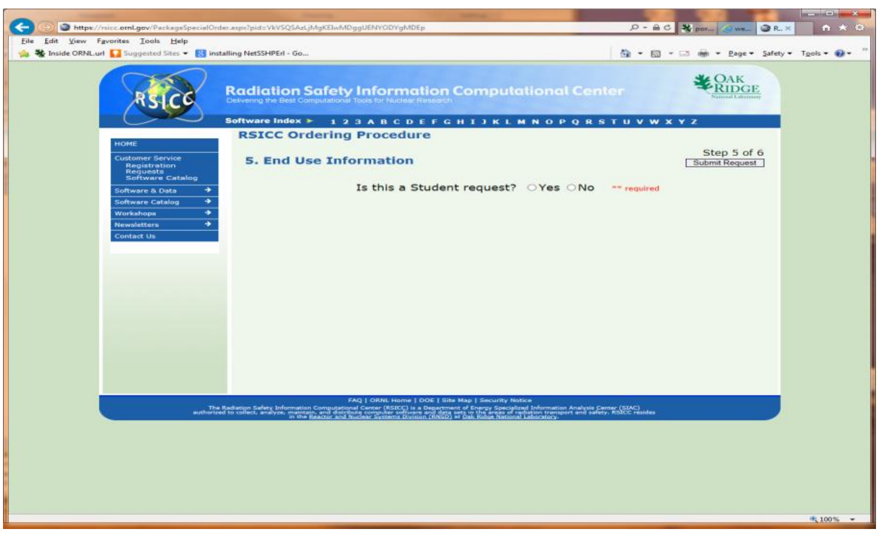
- Customers provide mailing and identification information.

Package Verification



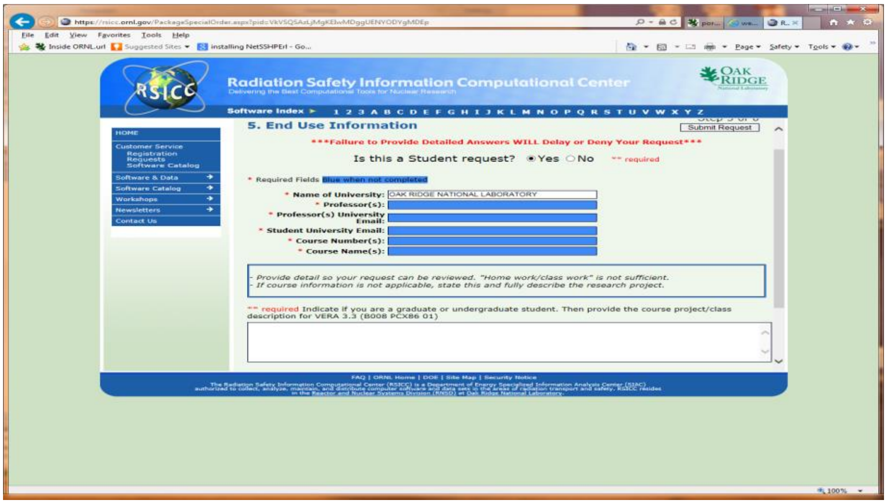
- Verify package.

End Use I



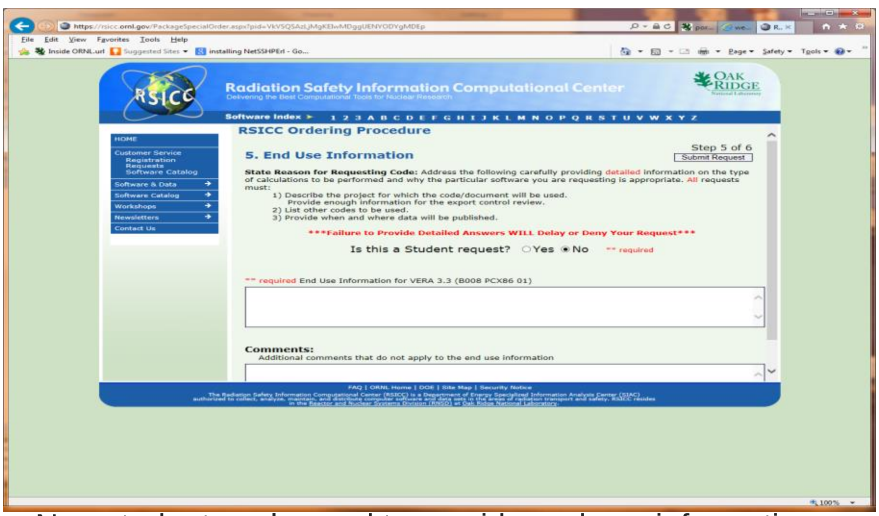
- Indicate if Student . This is for request processing and recovery fee assessment.

End Use II



- Student must provide course and instructor information.
- Usually no fees

End Use III



- Non-students only need to provide end use information
- Usually fees except for special programs

CASL approval for distributions

- Distribution to users is subject to CASL approval
  - Available under a Test & Evaluation license agreement
  - Limited support
- Criteria for approval
  - Appropriate export control, intellectual property, and licensing issues are addressed for that customer
  - The customer has a valid usage for VERA
  - Feedback from the customer is likely to inform future VERA development efforts

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http://www.casl.gov

NuScale Power:
Status and CASL Engagement

Daniel Ingersoll

Director, Research Collaborations

CASL Industry Council

November 4-5, 2015

NuScale Nonproprietary

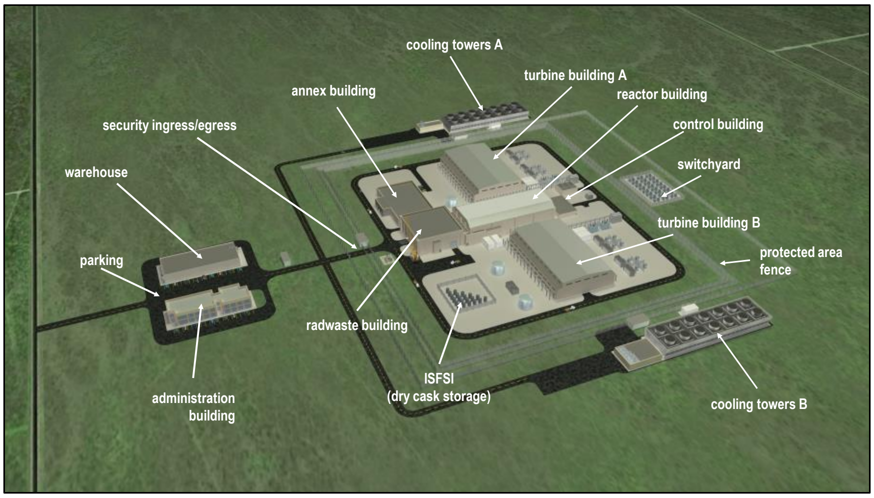
NuScale Power™

- Fluor has invested ~$300MM since October 2011
- DOE initiated a Cooperative Agreement grant in May 2014
  - $217M matching funds over 5 years
- Several additional strategic partners have joined the team
- ~600 FTE's currently on project
  - >260 NuScale employees
- Now operate 7 offices (Portland, Corvallis, Rockville, Charlotte, Idaho Falls, Richland, London)

NuScale Engineering Offices Corvallis

NuScale Integral Simulator Test

NuScale Control Room Simulator



Aerial view of 12-module NuScale plant

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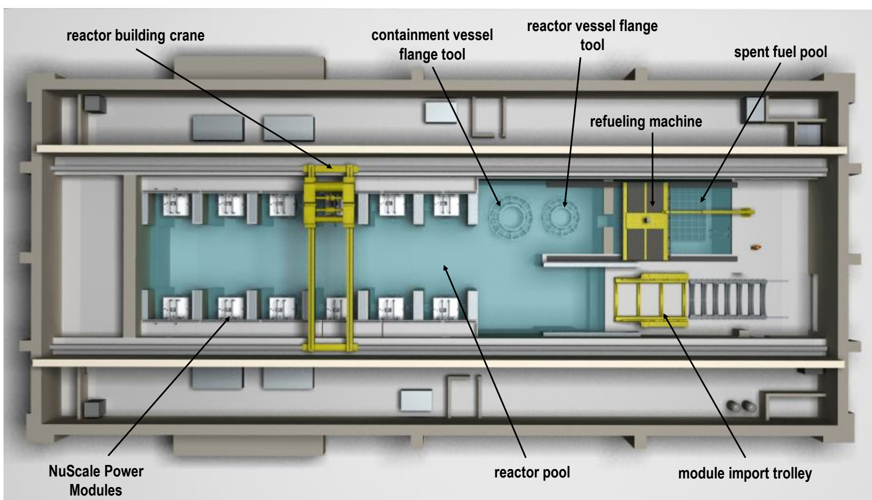

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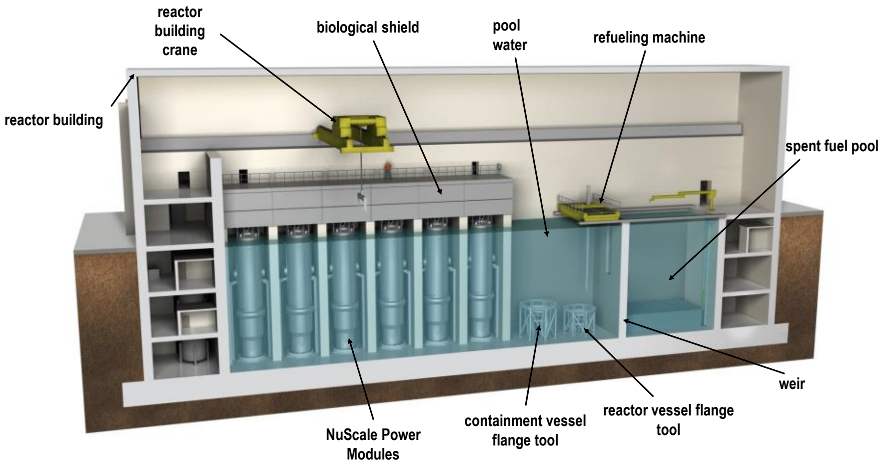
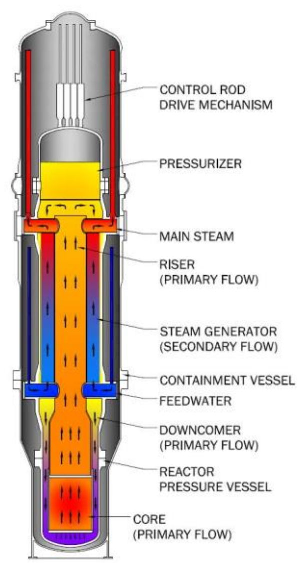
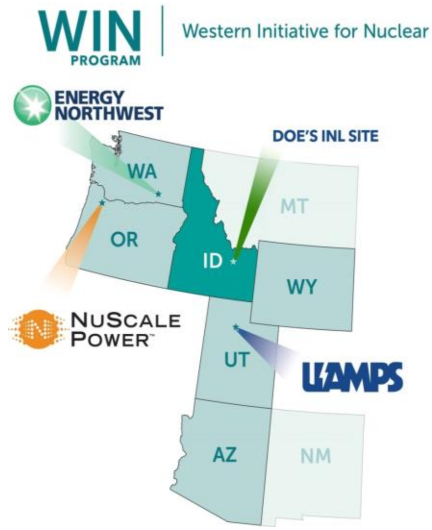
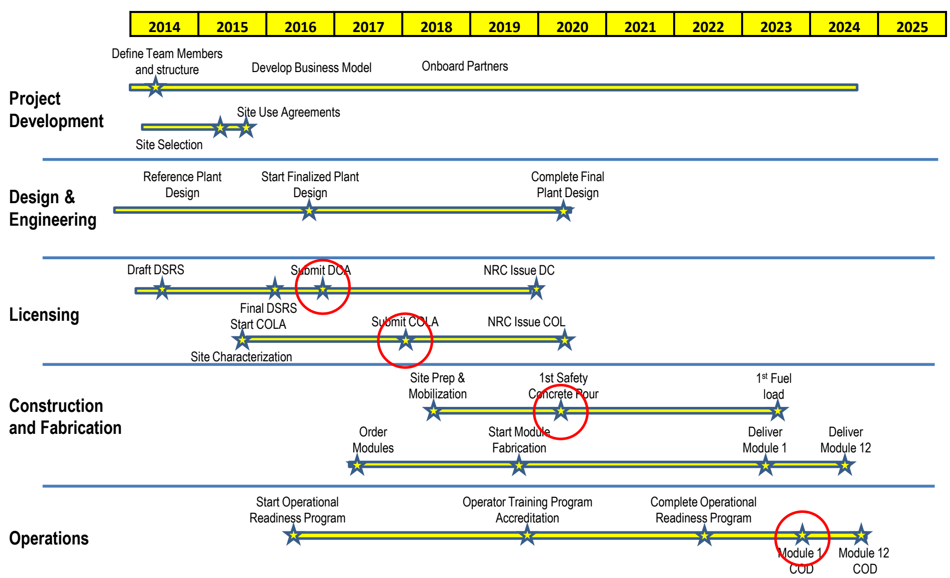


- Integrated reactor vessel
  - steam generator, pressurizer, fuel inside a single vessel
- Natural circulation flow
  - no reactor coolant pumps
  - no external power
- High-pressure steel containment
  - Allows simplified emergency core cooling system
  - Provides decay heat removal path
- Traditional LWR fuel, materials, and water chemistry



- Multi-western state collaboration to pursue the demonstration and deployment of NuScale plants
- Initial participants: NuScale, UAMPS, Energy Northwest, ID, UT, OR, WA, WY, AZ
- First commercial project:
  - Multi-module NuScale plant
  - Potentially located within the Idaho National Laboratory Site
  - Owned by UAMPS
  - Operated by Energy Northwest
  - Target operations: 2023

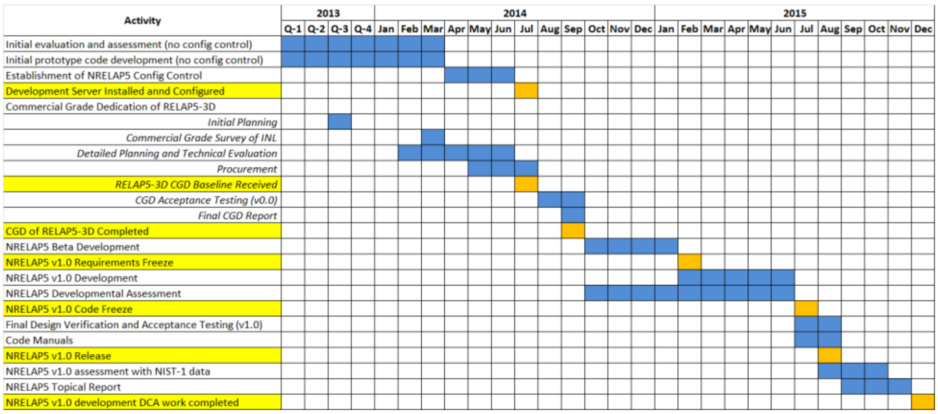




- Model phenomena that are most important and unique to our system design
  - Natural circulation in iPWR reactor vessel (0-100% power)
  - Coolant flow phenomena on both sides of internal steam generator (helical tubes)
  - Heat transfer to ultimate heat sink (radial and axial)
  - Very long cool-down phenomena
- Already participating in NEAMS/HIP project for SG FIV
- Intend to pursue VERA Test Stand
- Caveats:
  - Experimental validation is critical for NRC acceptance
  - Development of NQA1 software is time-consuming and expensive

Test/Demonstration Program	Test Facility	Status
Critical Heat Flux Test – Phase 1	Stern Lab, Canada	Completed
Steam Generator Tube Inspection Feasibility Study	Corvallis, Oregon	Completed
SIET TF1; 3-Coil, Full-Length, Electrically Heated Steam Generator Tests	SIET, Piacenza, Italy	Completed
SIET TF2; 252-Coils, full length, Prototypic Fluid-to-Fluid heat transfer	SIET, Piacenza, Italy	Completed
Upper Module Mock-up	OIW, Vancouver, WA	Completed
NIST-1 Facility; Integral System Testing	OSU, Corvallis, Oregon	Underway
CRD Shaft Alignment and CRA Drop Testing	Erlangen, Germany	Underway
Fuel Mechanical and Hydraulic Testing	Richland, WA	Underway
Steam Generator Flow Induced Vibration	Erlangen, Germany	Underway
CRA/CRAGT Flow Induced Vibration	Erlangen, Germany	Planning
Core Inlet Flow Distribution	TBD	Planning
Critical Heat Flux Test – Phase 2 (Fuel Specific)	Karlstein, Germany	Planning

- Extensive effort needed to develop NRELAP5
  - About 40,000 man-hours (20 man-years) from 2013-2015



- Initial dialog with engineering and safety analysis staff generated several potential test stand options:
  - CRUD performance in natural circulation cores
  - Boron distribution characteristics in natural circulation coolant systems
  - Low-flow critical heat flux behavior
  - Long-term cool-down effects
  - Pellet-clad interaction behavior during flexible power operations

- Next step is to arrange telecom with NuScale experts and CASL staff to:
  - Discuss simulations of priority to NuScale
  - Review readiness and adaptability of VERA components
  - Select a test stand challenge problem
  - Assign roles for development of a test stand project plan

- Higher fidelity simulation to understand margins more accurately
  - Potentially support power uprates and future design improvements
- Balance of plant modeling to improve power conversion efficiency
- Dynamic systems modeling to support co-generation and hybrid energy applications

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